Geoneutrinos

Livia Ludhova

Istituto Nazionale di Fisica Nucleare
Milano, Italy

Underground Synergies with
Astro-Particle Physics
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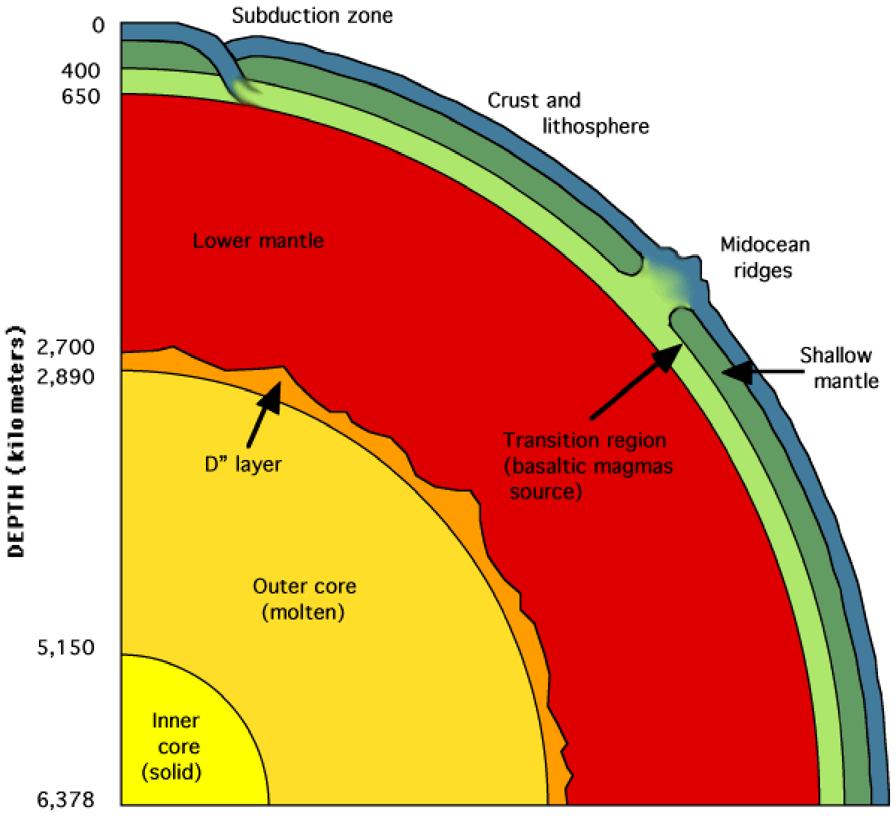
Outline

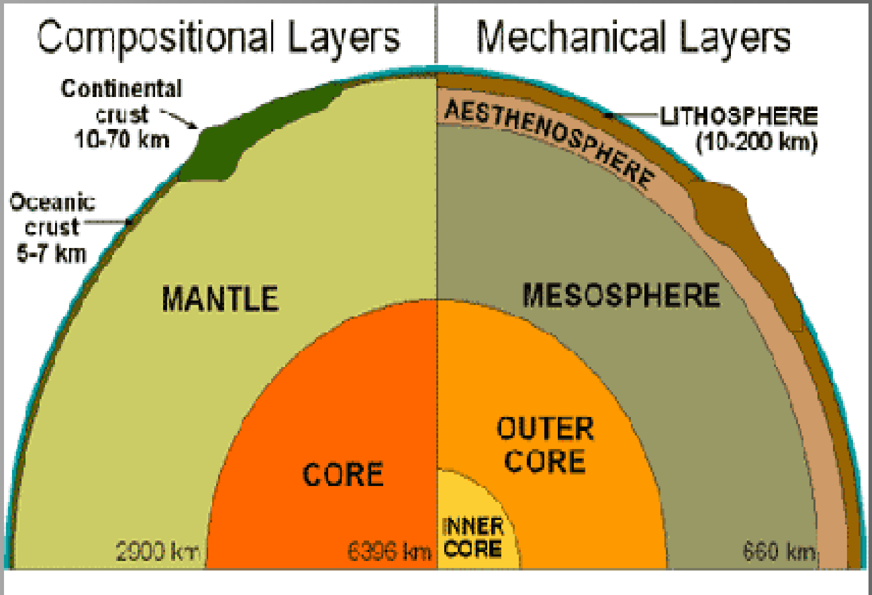
- **The Earth** **(mostly for non-geoscientists)**
- **Neutrinos and anti-neutrinos** **(mostly for non-physicists)**
- **Geoneutrinos**
- **Current experiments and latest geoneutrino experimental results**
- **Future prospects**

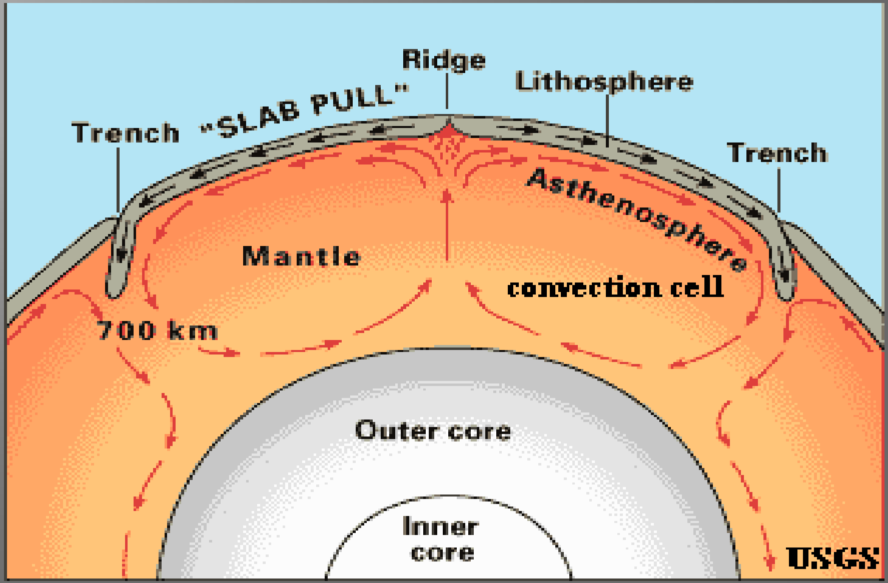
Outline

- **The Earth** **(mostly for physicists)**

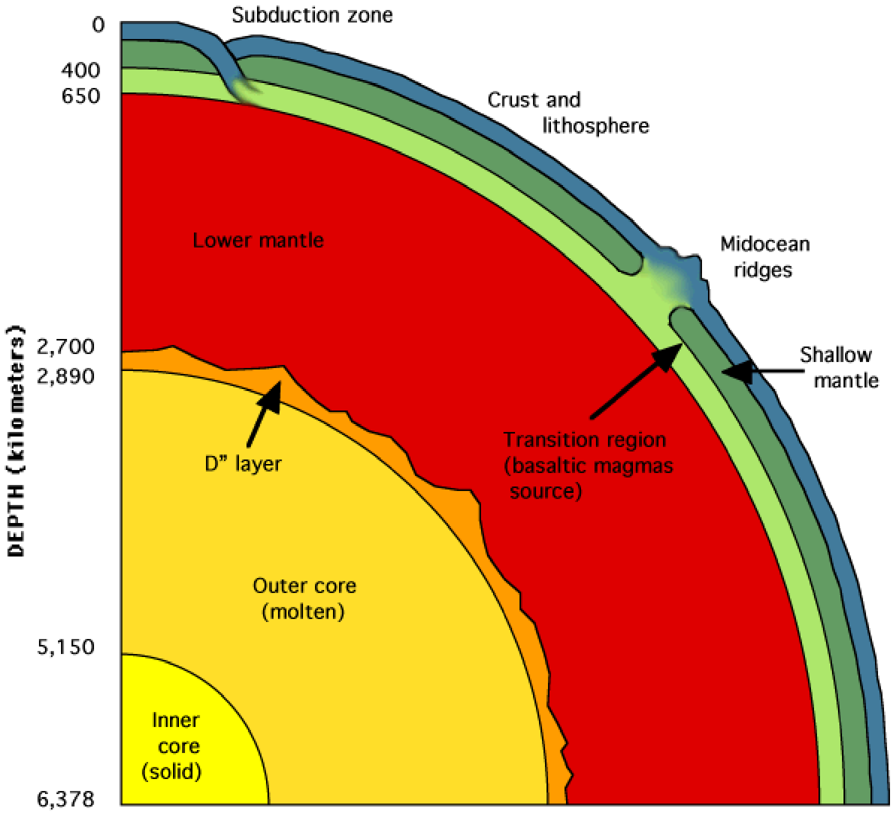
Earth structure







Earth structure



Inner Core - SOLID

- about the size of the Moon;
- Fe – Ni alloy;
- <u>**solid**</u> (high pressure ~ 330 GPa);
- temperature ~ 5700 K;

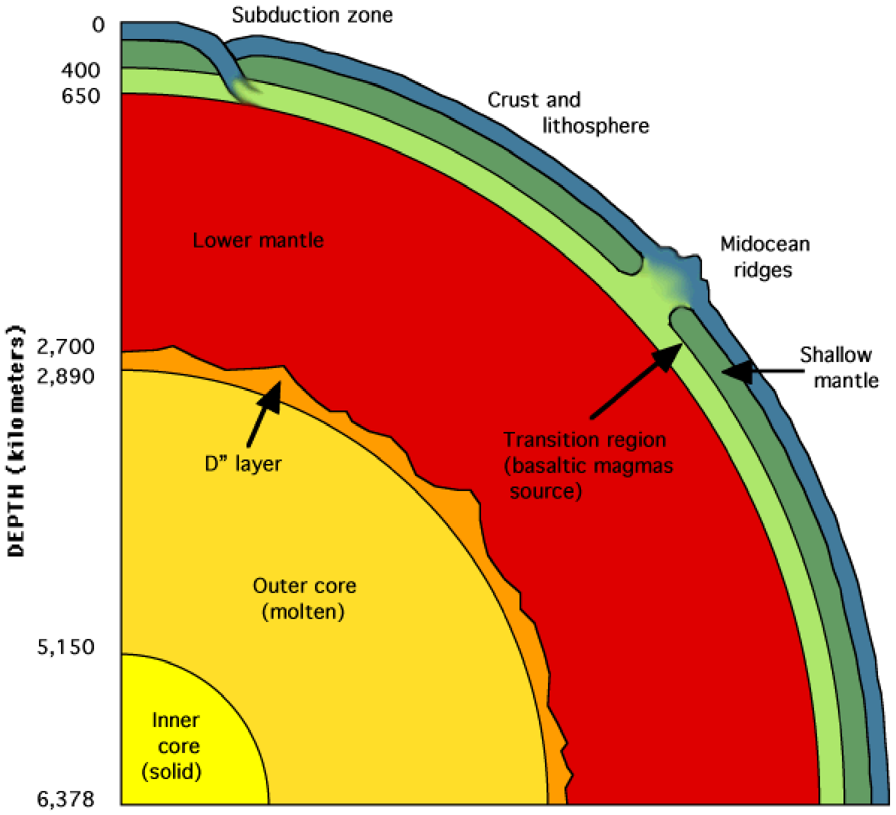
Outer Core - LIQUID

- 2260 km thick;
- FeNi alloy + 10% light elem. (S, O?);
- <u>**liquid;**</u>
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid within the Sun’s magnetic field;

D’’ layer: mantle –core transition

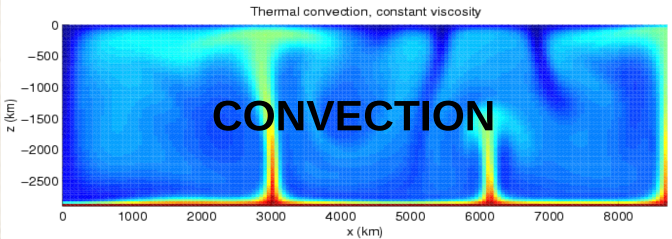
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

Earth structure



Lower mantle (mesosphere)

- rocks: high Mg/Fe, < Si + Al;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- "plastic" on long time scales:

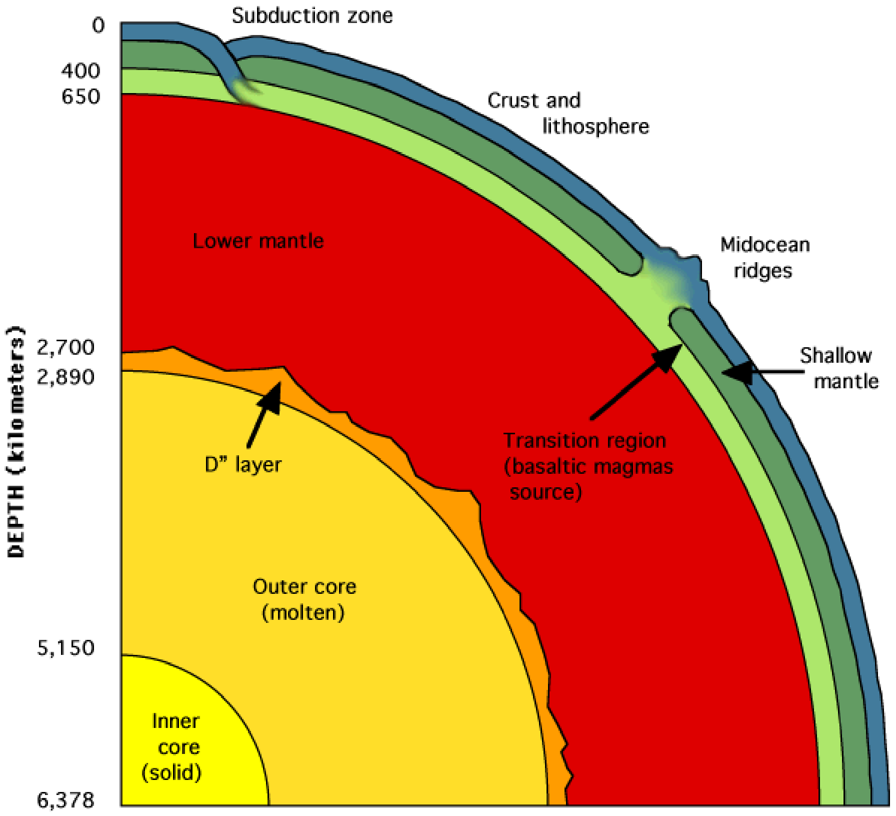


Transition zone (400 -650 km)

seismic discontinuity;

- mineral recrystallisation;
- : role of the latent heat?;
- partial melting: the source of mid-ocean ridges basalts;

Earth structure



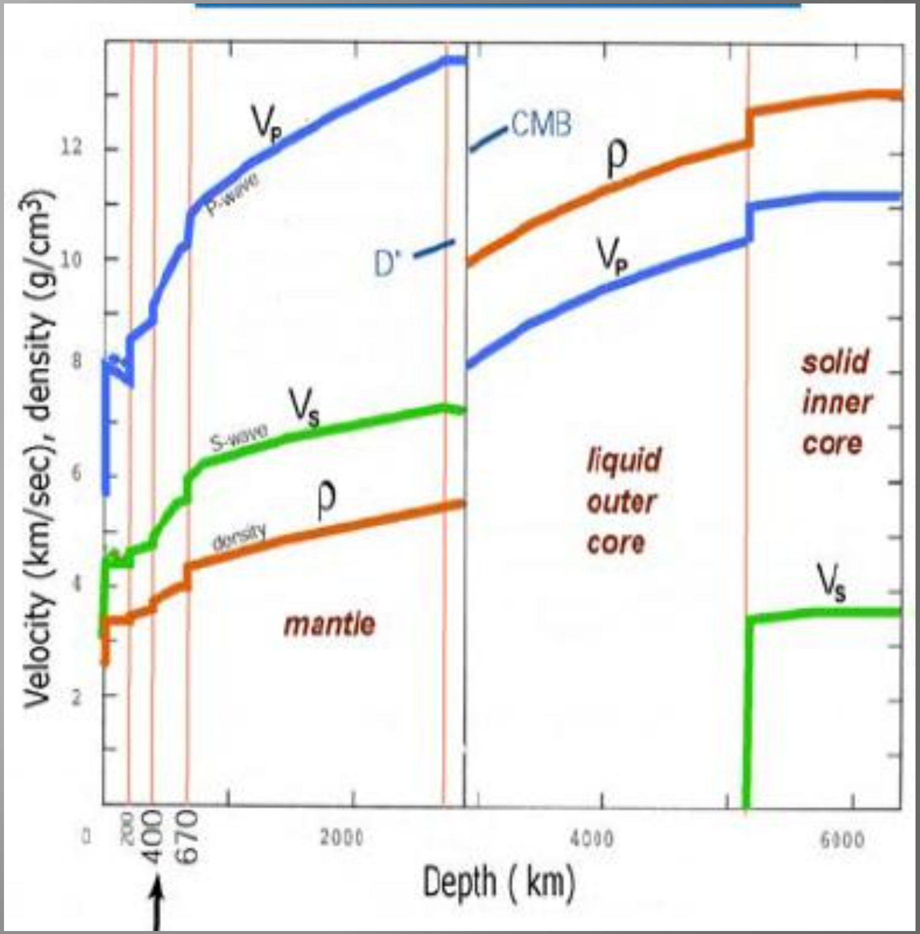
Upper mantle

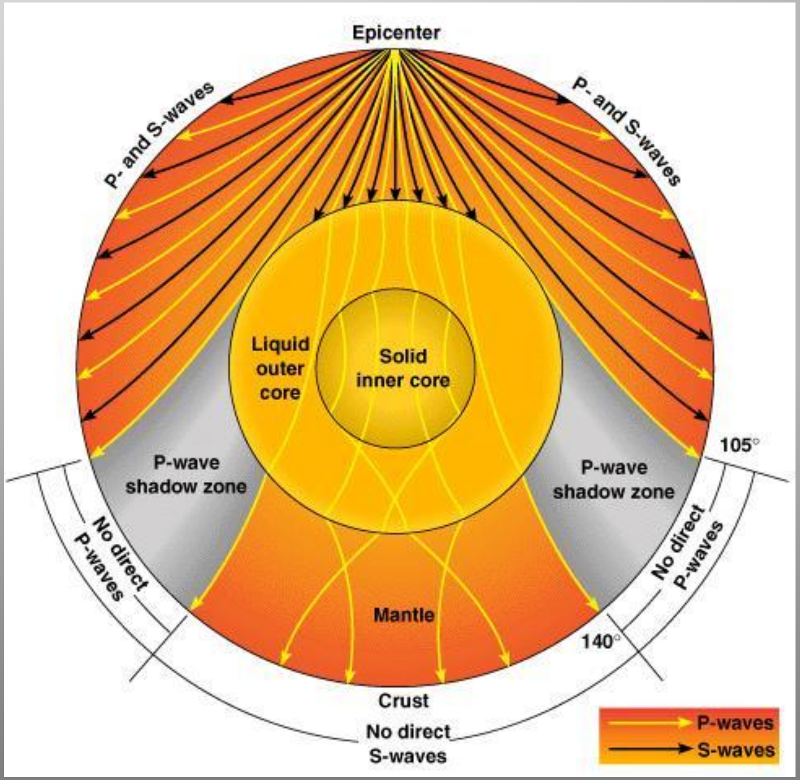
- composition: rock type peridotite
- includes highly viscose **astenosphere** on which are floating litospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);

Crust: the uppermost part

- **OCEANIC CRUST**:
- created at mid-ocean ridges;
- ~ 10 km thick;
- **CONTINENTAL CRUST**:
- the most differentiated;
- 30 – 70 km thick;
- igneous, metamorphic, and sedimentary rocks;
- obduction and orogenesis;

Seismology





Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

P – primary, longitudinal waves
S – secondary, transverse/shear waves

Geochemistry

1) **Direct rock samples**

* surface and bore-holes (max. 12 km);

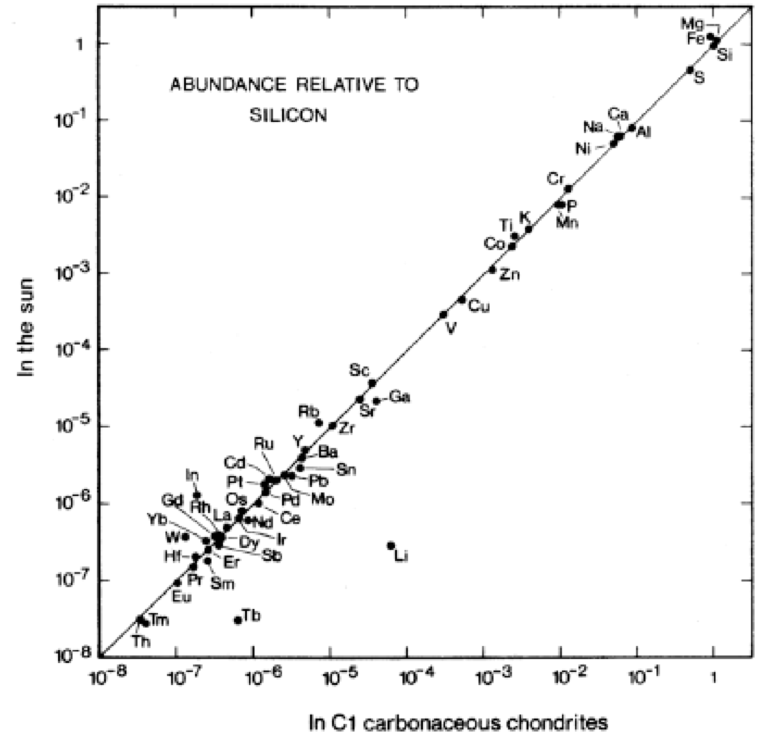
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

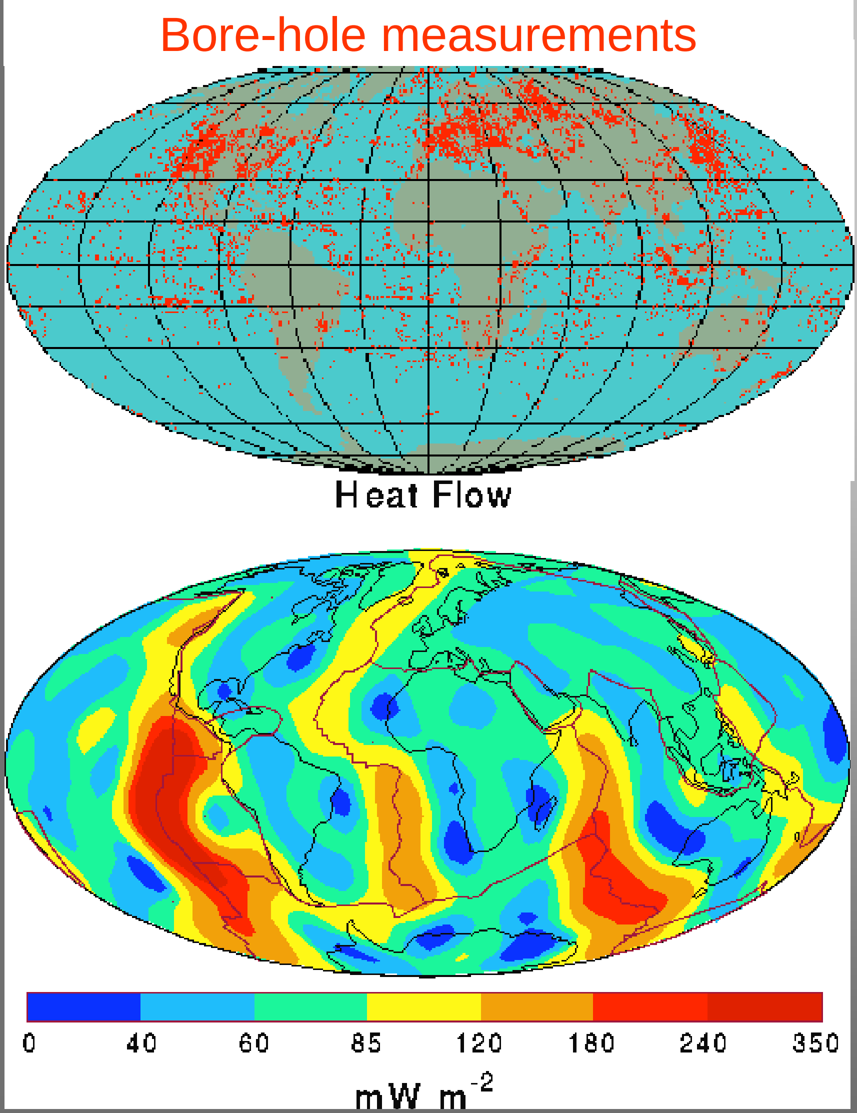
2) **Geochemical models:**

composition of direct rock samples +
C1 carbonaceous chondrites meteorites +
Sun's photosphere;

Bulk Silicate Earth (BSE) models (several!):
medium composition
of the "re-mixed" crust + mantle,
i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;



Surface heat flux



Global Heat Flow Data (Pollack *et al.*)

- Conductive heat flow from bore-hole temperature gradient;
- **Total surface heat flux:**

  31 ± 1 TW (Hofmeister&Criss 2005)

  46 ± 3 TW (Jaupart et all 2007)

  47 ± 2 TW (Davis&Davies 2010)

(same data, different analysis)

SYSTEMATIC ERRORS

Different assumptions concerning the role of fluids in the zones of mid ocean ridges.

Sources of the Earth heat

- **Total heat flow ("measured"): 31±1 or 46±3 or 47±2 TW**
- ***Radiogenic heat = from decays of radioactive elements***

  A) C1 carbonaceous chondrites : 17-21 TW from which

  ~9 TW from the crust and 0 from the core (the rest is in the mantle);

  B) Enstatic-chondrites models: (Javoy 2010): 11 TW!!!

- **Other heat sources (possible deficit up to 47-11 = 36 TW!)**
  - **Residual heat: gravitational contraction and extraterrestrial impacts in the past;**
  - **^{40}K in the core;**
  - **nuclear reactor; (BOREXINO rejects a power > 3 TW at 95% C.L.)**
  - **mantle differentiation and recrystallisation;**

IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

Outline

- **Neutrinos and anti-neutrinos (mostly for non-physicists)**

LEPTONS

particles - antiparticles

lepton number +1

lepton number -1

e^-	ν_e	e^+	$\bar{\nu}_e$
μ^-	ν_μ	μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ	τ^+	$\bar{\nu}_\tau$

3 flavors

ν_e produced in the nuclear reactions in the Sun;

Total flux ~10^{10} cm^{-2} s^{-1}

Detected via elastic scattering on e:

$\nu_e + e^- \rightarrow \nu_e + e^-$

$$\sigma_{\nu_e e^- \to \nu_e e^-} \approx 9.5 E_\nu(MeV) \times 10^{-45} \mathrm{cm}^2$$

$\bar{\nu}_e$ produced in the nuclear power-plants (< 10 MeV) and from the Earth radioactivity (**geoneutrinos**) (< 3 MeV)

Total geoneutrino flux ~10^6 cm^{-2} s^{-1}

$$\bar{\nu}_e + p \to e^+ + n.$$

$$\sigma_{\bar{\nu}_e p \to e^+ n} \approx 9.3 [E_\nu(MeV)]^2 \times 10^{-44} \mathrm{cm}^2,$$

Neutrino oscillations

Each (anti-) neutrino flavour, electron, muon, tau is a superposition of 3 mass eigenstates, 1, 2, and 3, in different and characteristics proportions.

An (anti-)neutrino of a given energy(momentum) represents a periodically evolving mixture of mass eigenstates, thus a probability to observe a certain flavor does oscillate during its passage.

The probability to detect electron antineutrino (from nuclear power plant or geo-neutrino) oscillates:

$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 \boxed{L}}{4\boxed{E}}\right)\right) + \sin^4\theta_{13}$$

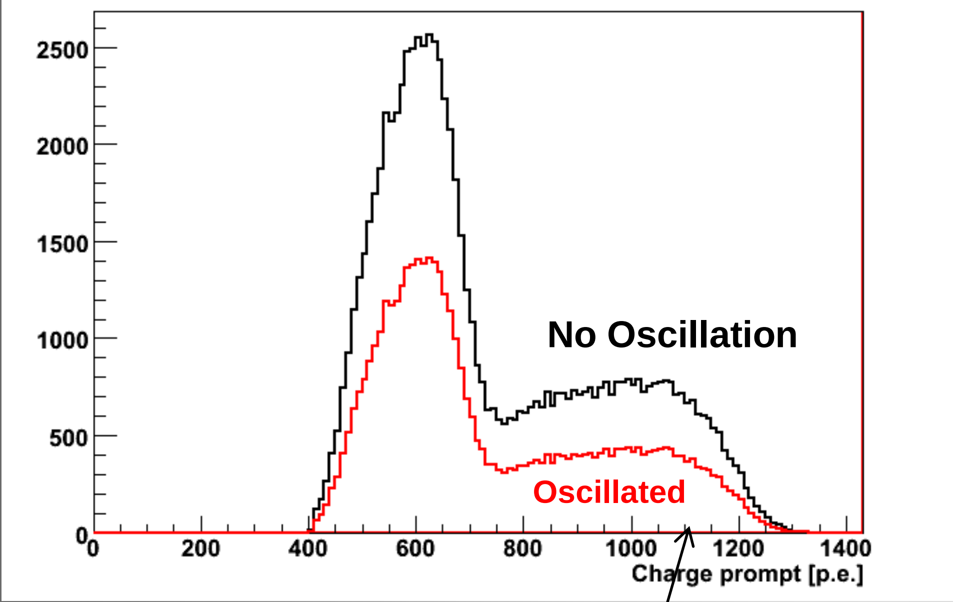
θ_{12}, $\theta_{13,}$ Δm_{12}^2 … physical constants (oscillation parameters)

$\sin^2\theta_{12} = 0.306 \pm 0.017$; $\sin^2\theta_{13} = 0.024 \pm 0.004$; $\delta m^2 = (7.6 \pm 0.2) \times 10^{-5}\ eV^2$

$\boxed{L}$… source – detection distance

$\boxed{E}$ ….antineutrino energy in MeV

Geoneutrinos



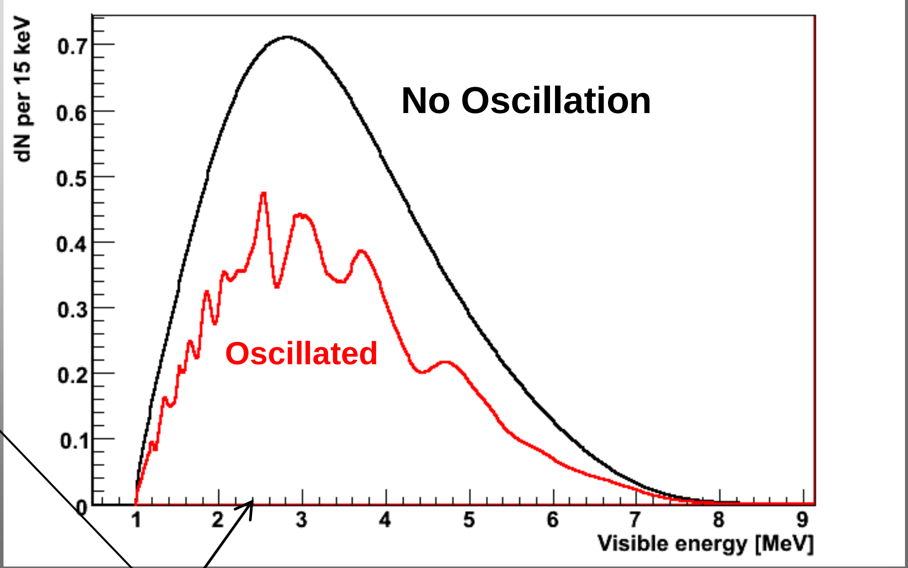
3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012),

but for reactor antineutrinos not!

E_antinu = 3 MeV

Reactor antineutrinos at LNGS



Outline

- Geoneutrinos

Geoneutrinos: antineutrinos from the Earth

- ***Electron antineutrinos from the decays of long lived radioactive isotopes naturally present in the Earth;***
- ^{238}U and ^{232}Th chains and ^{40}K ($T_{1/2}$ = (4.47, 14.0, 1.28) x 10^9 years, resp.):

$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- +$ 1 anti-neutrino + 1.32 MeV

Earth shines in antineutrinos: flux ~ 10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

(to compare: solar neutrino flux ~ 10^{10} cm^{-2} s^{-1})

the only direct probe of the deep Earth

released heat and anti-neutrinos flux in a well fixed ratio!

measure geoneutrino flux = (in principle) = get radiogenic heat

in practice (as always) more complicated…..

Geoneutrinos: why to study them

- **Possible answers to the questions**
  (most of them still far future though…) :
  - What is the radiogenic contribution to the terrestrial heat??
  - Are there any other heat sources or not?
  - What is the distribution of the long-lived radioactive elements within the Earth?
    - how much of them is in the crust and in the mantle;
    - Is their distribution in the mantle homogeneous or not;
    - are they present in the core;
    - is there a geo-reactor (Herndon 2001) ;
  - Are the BSE models compatible with geoneutrino data?
  - Discrimination among different BSE models;
  - What is the bulk Th/U ratio;

All these info would give significant margins to many geochemical and geophysical models and insights into the models of the Earth's formation.

Where is concentrated U, Th, and K ?

- The main long-lived radioactive elements: **^{238}U, ^{232}Th**, and **^{40}K**

U, Th, K are refractory lithophile elements (RLE)

- **Volatile /Refractory:** *Low/High condensation temperature*
- **Lithophile** – *like to be with silicates: during partial melting they tend to stay in the liquid part. The residuum is depleted. Accumulated in the continental crust. Less in the oceanic crust. Mantle even smaller concentrations. Nothing in core.*

concentration for ^{238}U
(Mantovani *et al*. 2004)

upper continental crust:	2.5	ppm
middle continental crust:	1.6	ppm
lower continental crust:	0.63	ppm
oceanic crust:	0.1	ppm
upper **mantle**:	6.5	**ppb**
core	NOTHING	

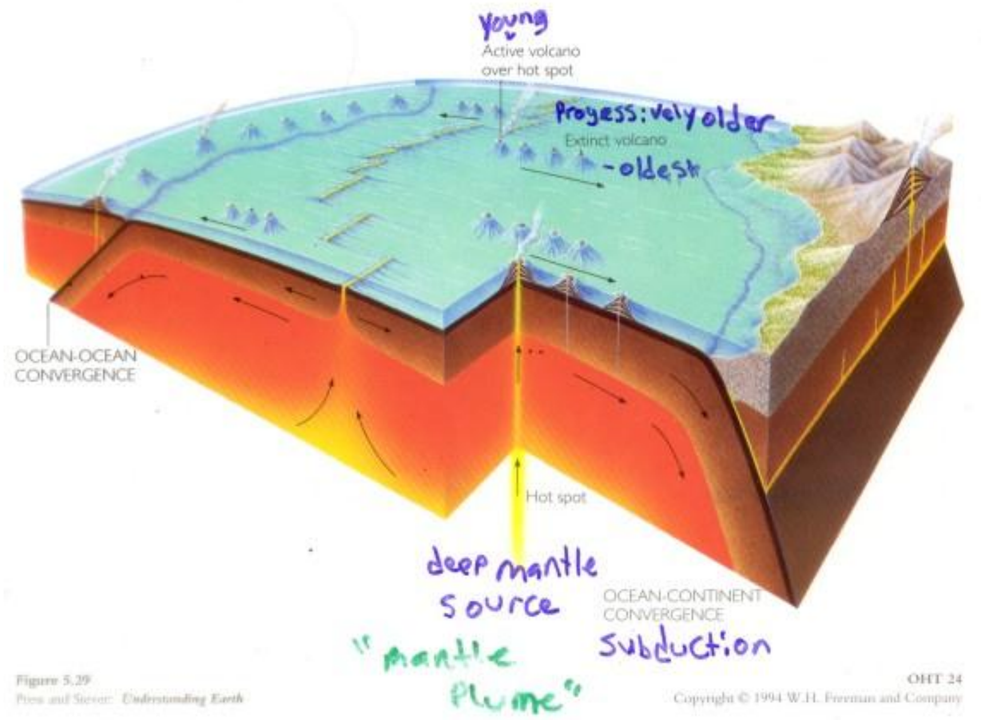


Figure 5.29
Press and Siever: *Understanding Earth*

OHT 24
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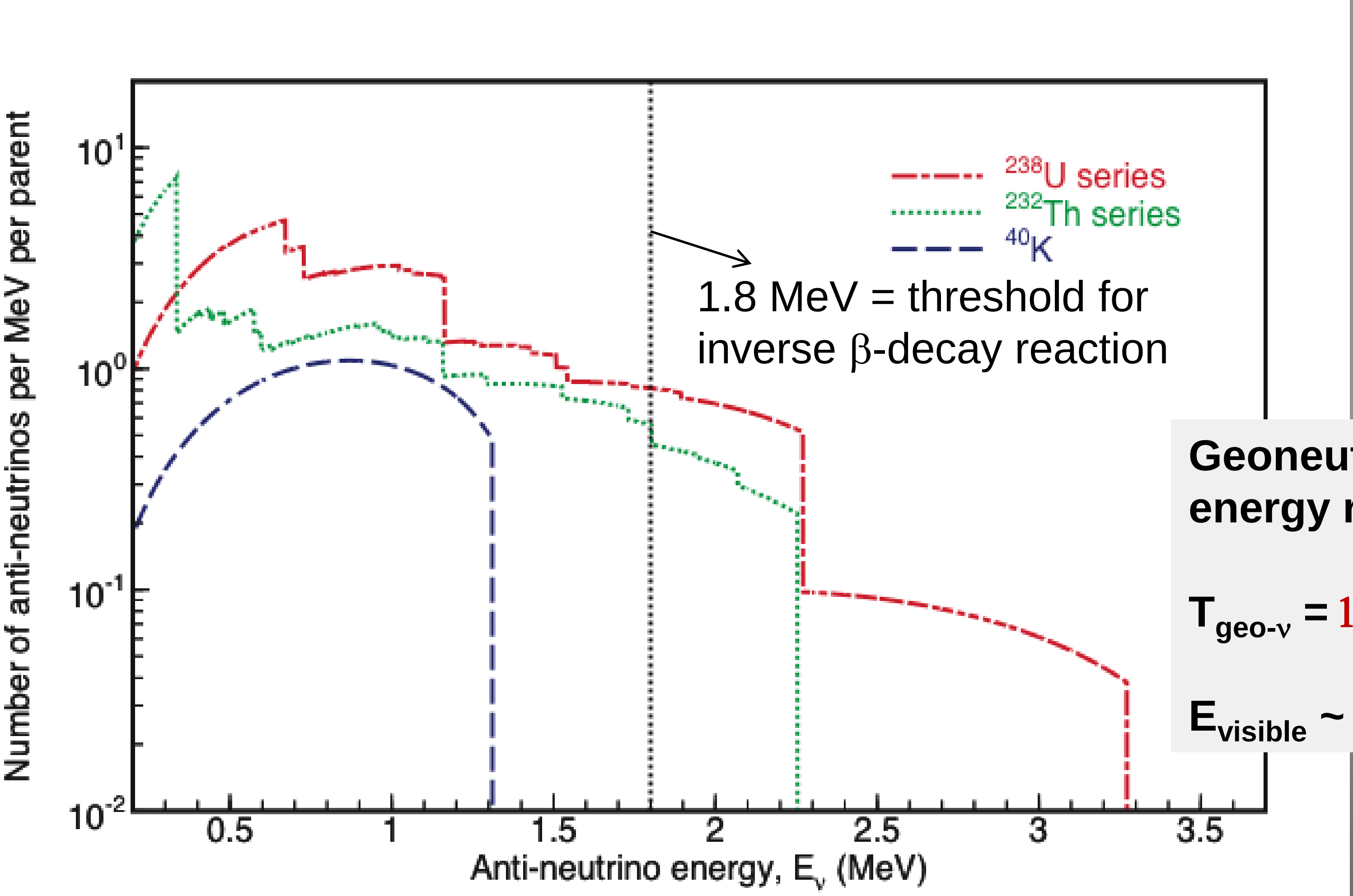
Geoneutrinos energy spectra

(theoretical calculations)



1.8 MeV = threshold for inverse β-decay reaction

Geoneutrinos energy range

$T_{geo\text{-}\nu}$ = 1.8 – 3.3 MeV

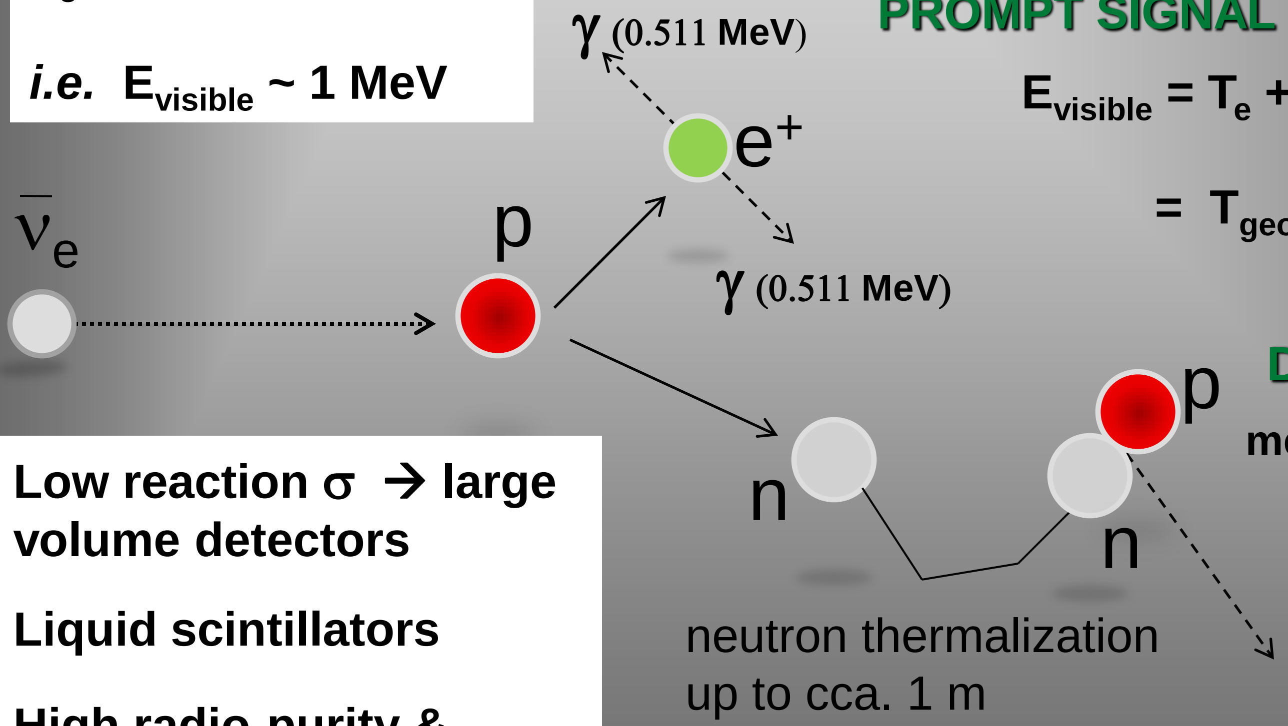
$E_{visible}$ ~ 1 – 2.5 MeV

Detecting geo-ν: inverse β-decay

Energy threshold of

$T_{geo\text{-}\nu}$ = 1.8 MeV

i.e. **$E_{visible}$ ~ 1 MeV**



PROMPT SIGNAL

$$E_{visible} = T_e + 2*0.511\ \text{MeV} =$$

$$= T_{geo\text{-}\nu} - 0.78\ \text{MeV}$$

DELAYED SIGNAL

mean n-capture time on p
256 μs

Low reaction σ → large volume detectors

Liquid scintillators

High radio-purity & underground labs to shield from cosmic rays

Outline

- **Current experiments and latest geoneutrino experimental results**

- **only 2 running experiments have measured geoneutrinos;**
- liquid scintilllator detectors;
- (Anti-)neutrinos have low interaction rates, therefore:
  - Large volume detectors needed;
  - High radiopurity of construction materials;
  - Underground labs to shield cosmic radiations;

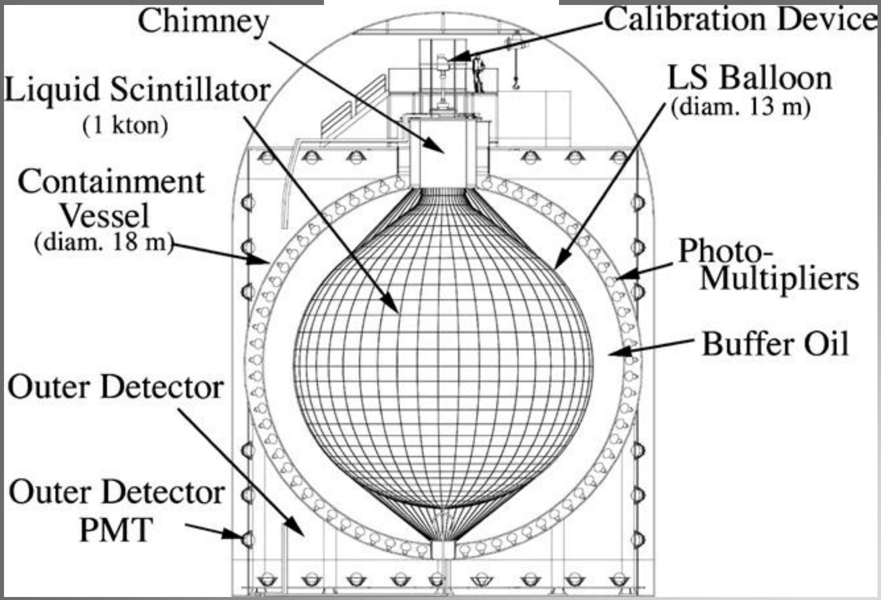
KamLand in Kamioka, Japan
Border bewteen
OCEANIC AND CONTINENTAL CRUST

- originally build to measure reactor antineutrinos;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- 2700 meters water equivalent shielding;

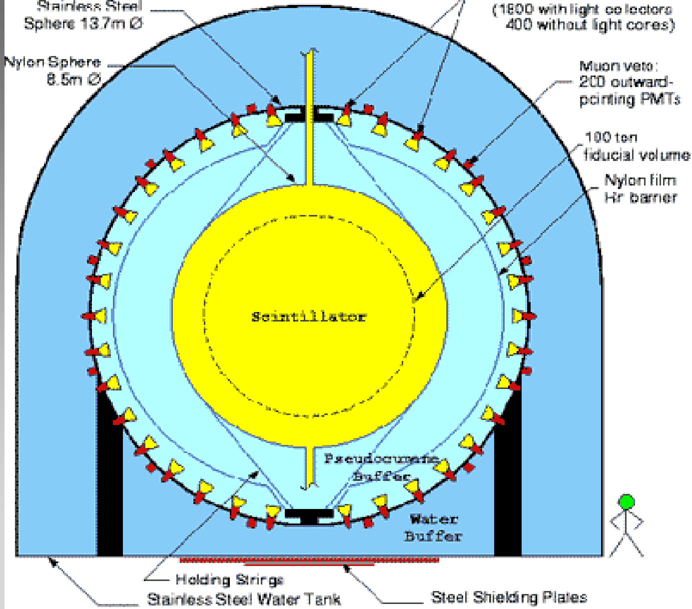
Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

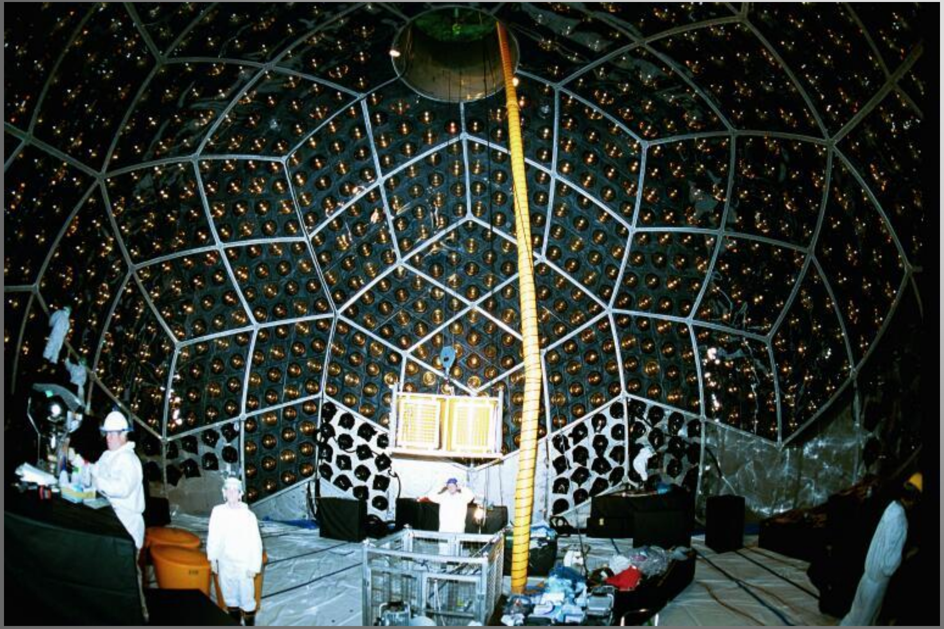
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

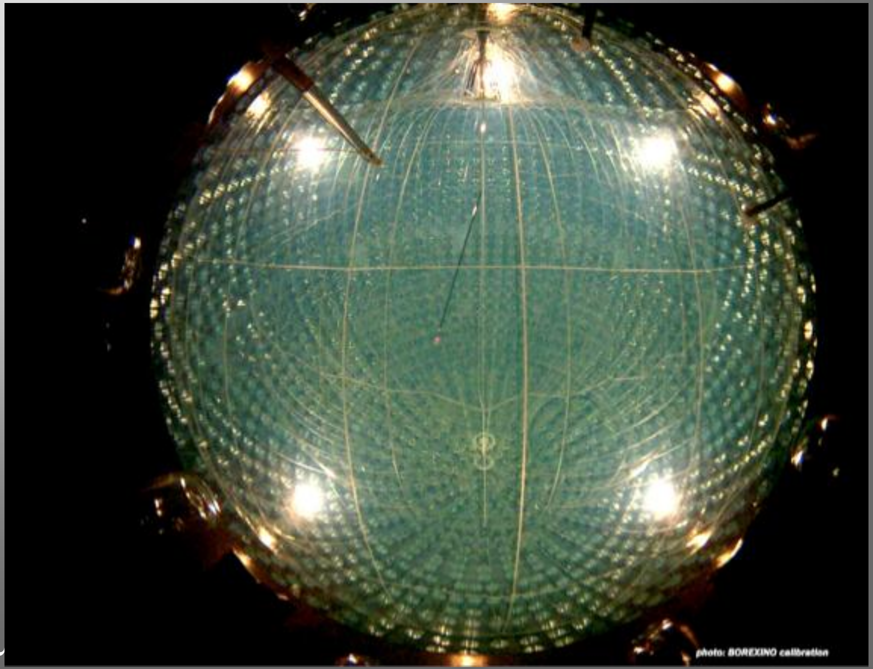
KamLand



Borexino







Experimental principle basics

antineutrino + proton → positron + neutron

E (prompt) = E(antineutrino) – 0.78 MEV

Edelayed = 2.2 MeV gamma

Δ time

Δ R

- **Charged particles produce scintillation light;**
- **Gamma rays from the positron annihilation and from the neutron capture are neutral particles but in the scintillator they interact mostly via Compton scattering producing electrons = charged particles;**
- **Scintillation light is detected by an array of phototubes (PMTs) converting optical signal to electrical signal;**
- **Number of hit PMTs = function (energy deposit) -> Eprompt, Edelayed**
- **Hit PMTs time pattern = position reconstruction of the event -> Δ R** of events
- Each trigger has its GPS time -> **Δ time** of events

We have then golden candidates found as time and spatial coincidences

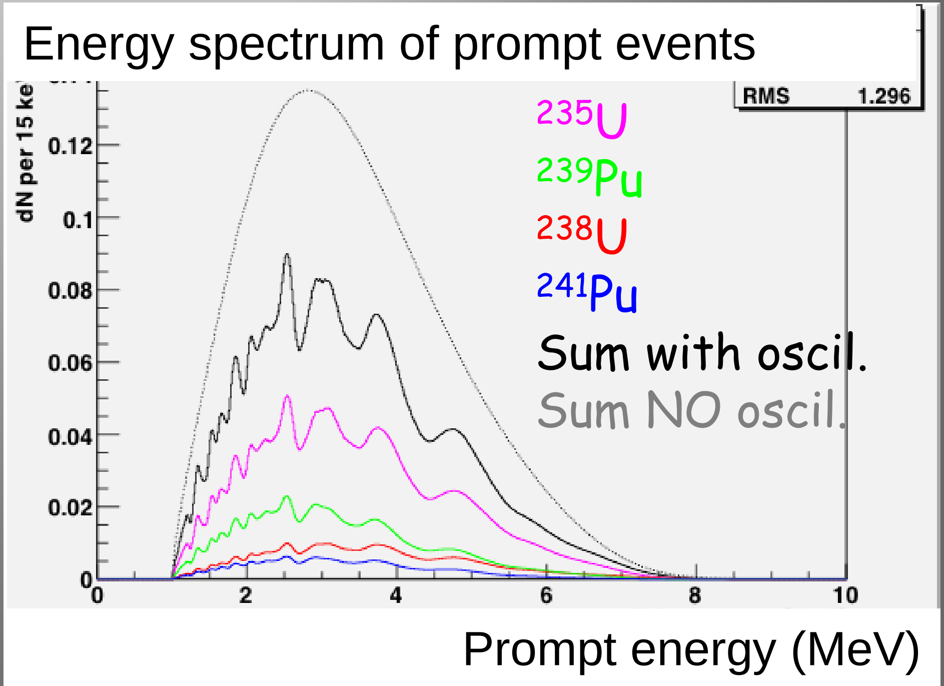
- They can be due to:
  - Geo-neutrinos;
  - Reactor antineutrinos;
  - Other backgrounds;
- We need to estimate different contributions and then extract the number of measured geo-neutrinos by fitting the Eprompt energy spectrum;

Expected reactor anti-neutrino signal and its error in Borexino

Φ_ν (E_ν>1.8 MeV)= (9.0 ±0.5)10^4 cm^{-2}s^{-1} → **(5.7±0.3) events/yr/100 t**

σ~10^{-44} cm^2 $N_{protons}$ = 6x10^{30} in 100 tons

Source of error	**Error (%)**
Oscillations: Δm^2	±0.02%
Oscillations: ϑ_{12}	**±2.6%**
Energy per fission of isotope i: E_i	±0.6%
Flux shape: $\Phi_i(E_\nu)$	**±2.5%**
Cross section: $\sigma(E)$	±0.4%
Thermal power: P_{rm}	**±2%**
Long lived isotopes in spent fuel	±1%
Fuel composition: f_{ri}	**±3.2%**
Reactor – Borexino distance L_r	±0.4%
TOTAL	**±5.38%**



Summary of backgrounds in Borexino

Background source	events/(100 ton-year)
Cosmogenic ^{9}Li and ^{8}He ✖	0.03 ± 0.02
Fast neutrons from μ in Water Tank (measured)	< 0.01
Fast neutrons from μ in rock (MC)	< 0.04
Non-identified muons	0.011 ± 0.001
Accidental coincidences ✖	0.080 ± 0.001
Time correlated background	< 0.026
(γ,n) reactions	< 0.003
Spontaneous fission in PMTs	0.003 ± 0.0003
(α,n) reactions in the scintillator [^{210}Po] ✖	0.014 ± 0.001
(α,n) reactions in the buffer [^{210}Po]	< 0.061
TOTAL	0.14 ± 0.02

We expect ~2.5 geo-ν/(100ton-year) (assuming BSE)

Latest geoneutrino experimental results

KamLand

high exposure: 99.997 CL observation in 2011 (Gando et al, Nature Geoscience 1205)

106 $^{+29}_{-28}$ geonu events detected;

(March 2002 – April 2009)
exposure 3.49 x 10^{32} target-proton year

Borexino

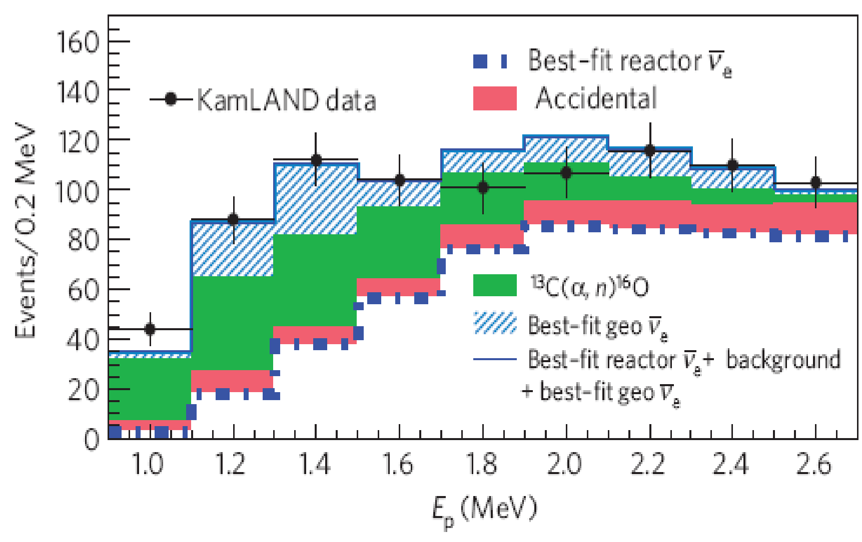
small exposure but low background level: observation at 99.997 CL in 2010 (Bellini et al, PLB 687):

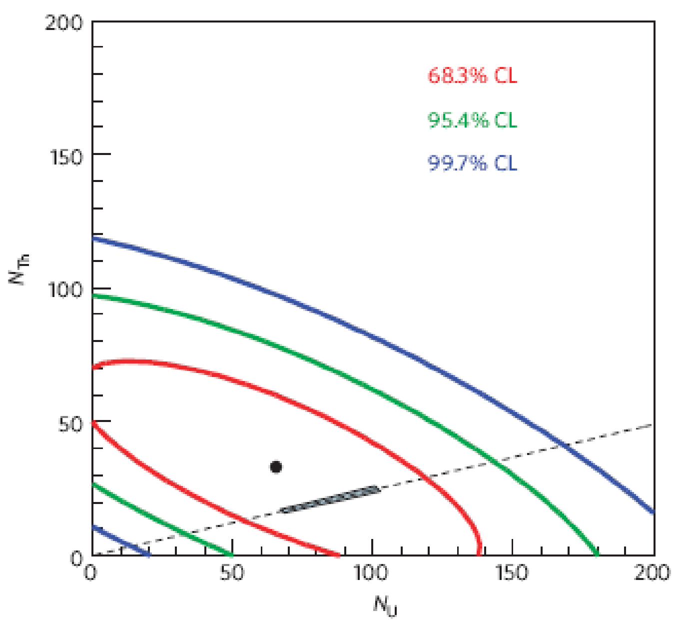
9.9 $^{+4.1}_{-3.4}$ geonu events detected;

(December 2007 – December 2009)
Exposure 0.15 x 10^{32} target-proton year

- active geo-reactor in the Earth core of power > 3 TW excluded at 95% CL;

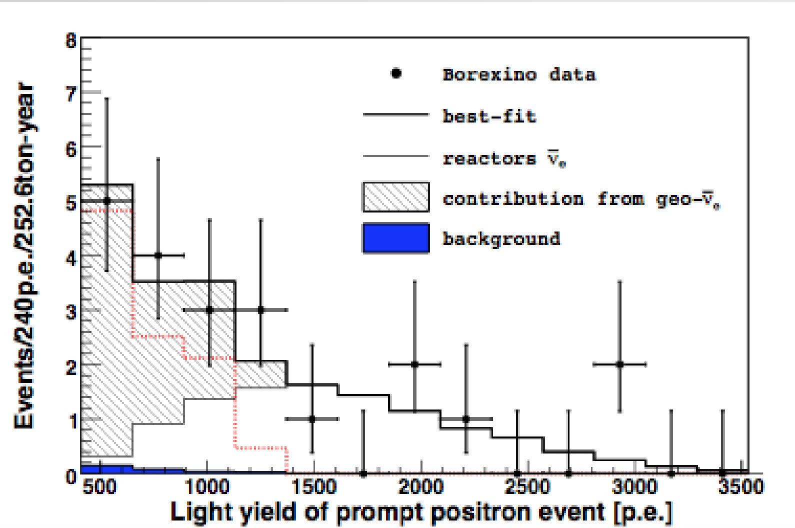
KamLand





A. Gando *et al*., Nature Geoscience **1205** (2011).

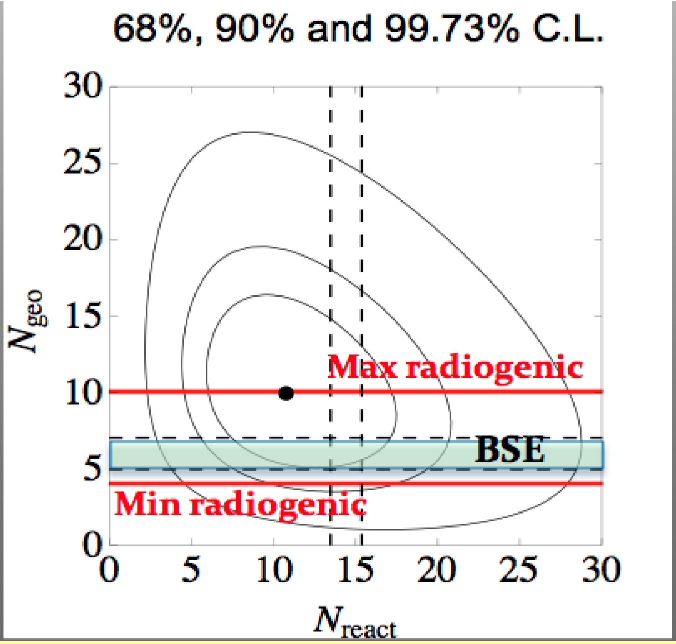
Borexino



~1 MeV

~3 MeV

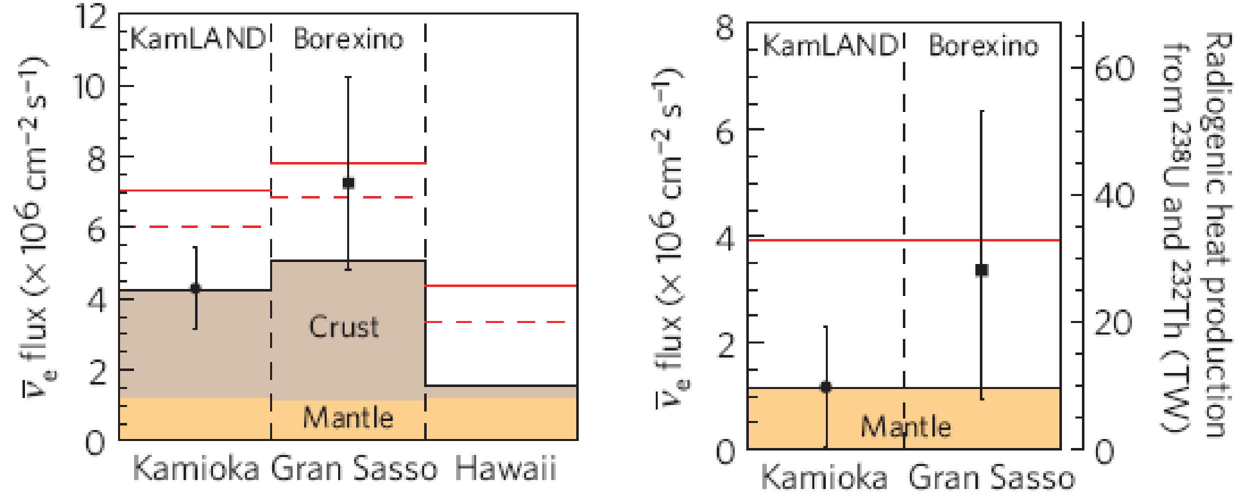
~7 MeV



G. Bellini *et al*., *PLB* **687** (2010) 299-304.

Combined analysis

A. Gando *et al*., Nature Geoscience **1205** (2011).



- **indication of mantle contribution ;**

•Fully radiogenic model excluded at 97% CL (CAREFULL WITH ASSUMPTIONS!)

(combined KamLand + Borexino data: uranium-238 and thorium-232: 20.0$^{+8.8}_{-8.6}$ TW, from geology: potassium-40 contributes 4 TW)

Combined analysis

G. Fiorentini et al.: Mantle Geoneutrinos in Kamland and Borexino, arXive 1204.1923

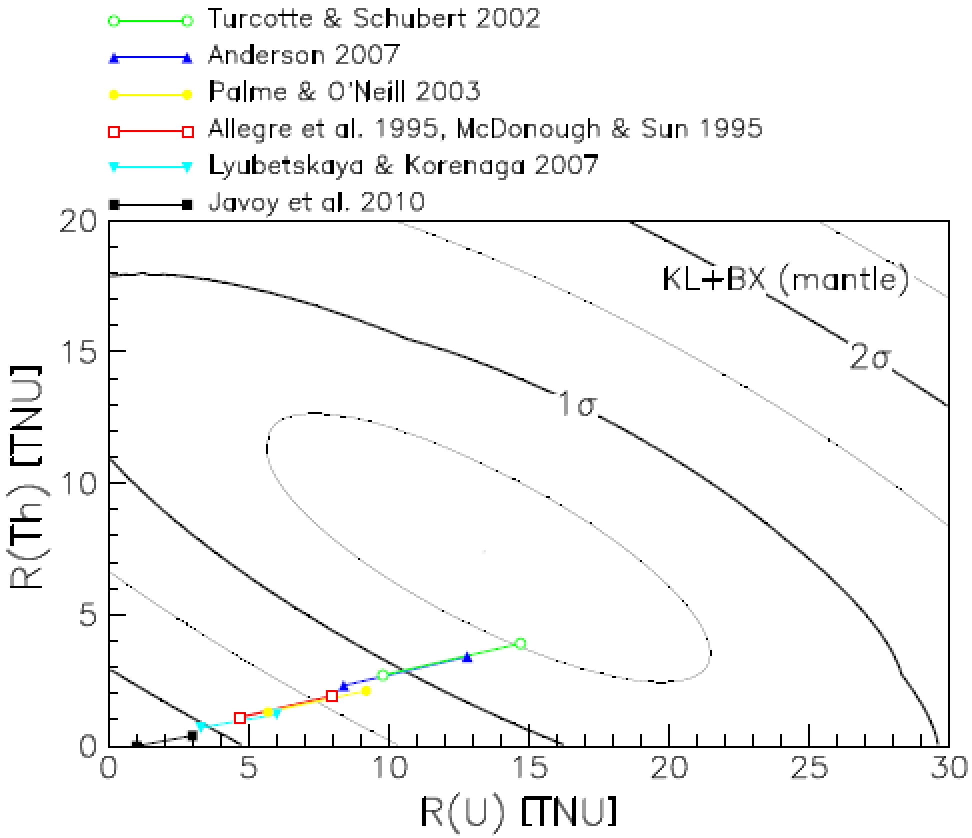


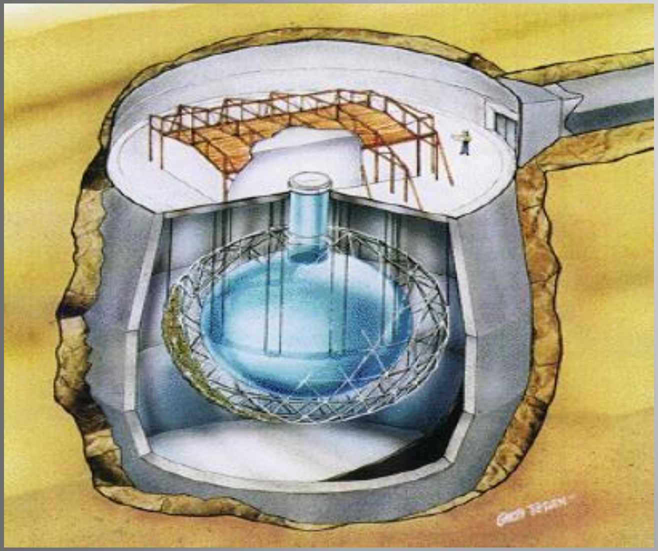
FIG. 4: Comparison of experimental constraints and model predictions in the plane charted by the Th and U mantle rates. Each model leads to extremal case of "low" and "high" rates, connected by lines to guide the eye. The KL+BX constraints are shown as $n\sigma$ contours in steps of 0.5σ. See the text for details.

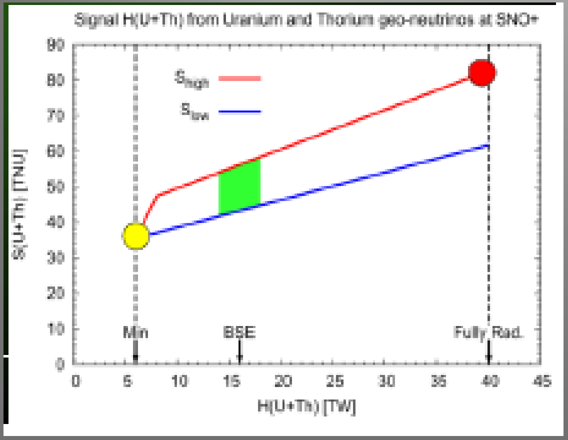
No mantle Geoneutrinos Disfavoured at > 2 sigma

Outline

- **Future**

SNO+ at Sudbury, Canada





Mantovani et al., TAUP 2007

SHOULD BE COMING SOON!

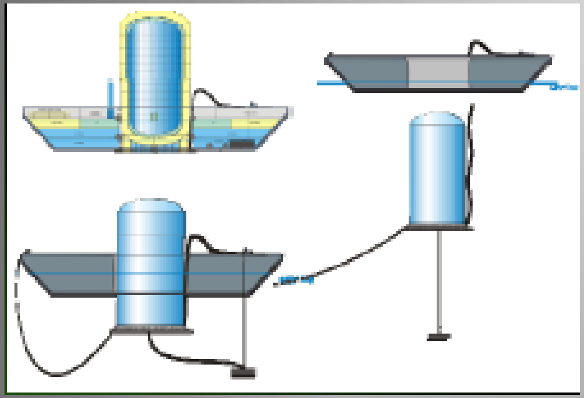
After SNO: D_2O replaced by 1000 tons of liquid scintillator
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

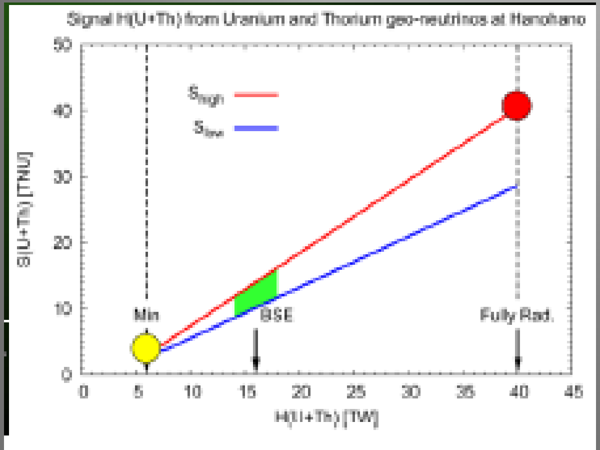
Placed on an old continental crust: 80% of the signal from the crust (Fiorentini et al., 2005)

BSE: 28-38 events/per year

Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent" in Hawaiian





Mantovani , TAUP 2007

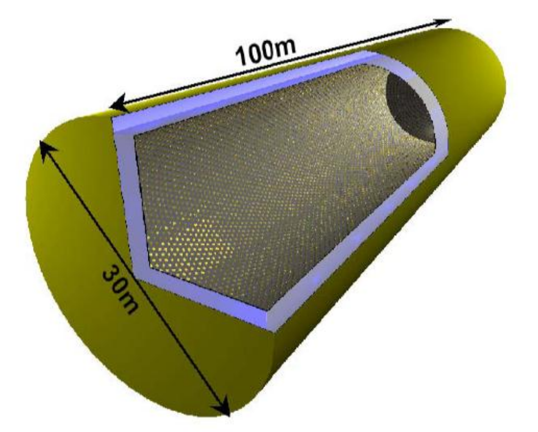
Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

Since Hawai placed on the U-Th depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year

LENA at Pyhasalmi, Finland

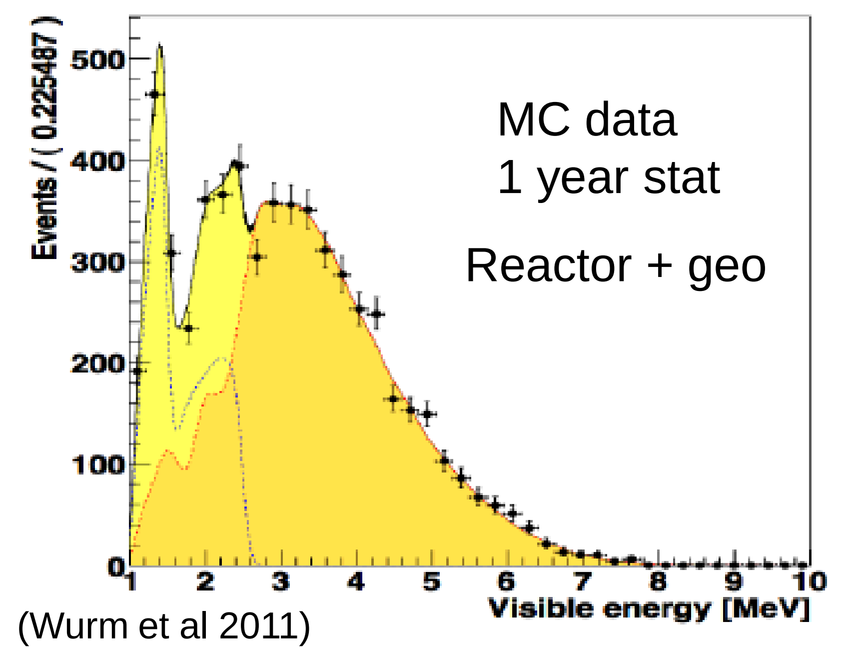


Project for a 50 kton underground liquid scintillator detector (Hochmuth et al 2007)

80% of the signal from the continental crust (Fiorentini et al.)
BSE: 800-1200 events/per year

Within the first few years, the total geoneutrino flux could be measuered at few % precision

Strong potential in determining the U/Th ratio of the measured geonu flux



MC data
1 year stat

Reactor + geo

(Wurm et al 2011)

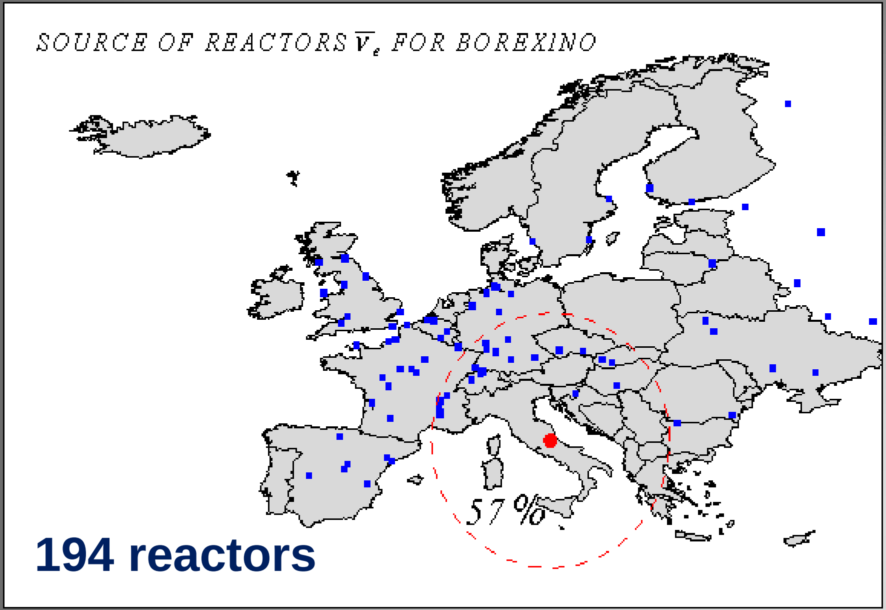
Summary

- The new interdisciplinary field is born;
- Collaboration among geologists and physicists is a must;
- The current experimental results confirm that geo-neutrinos can be successfully detected;
- Signal prediction and data interpretation: local geology around the experimental site must be studied;
- The combined results from different experimental sites have stronger impact – first geologically significant results start to appear;
- New measurements and the new generation experiments are needed for geologically highly significant results;

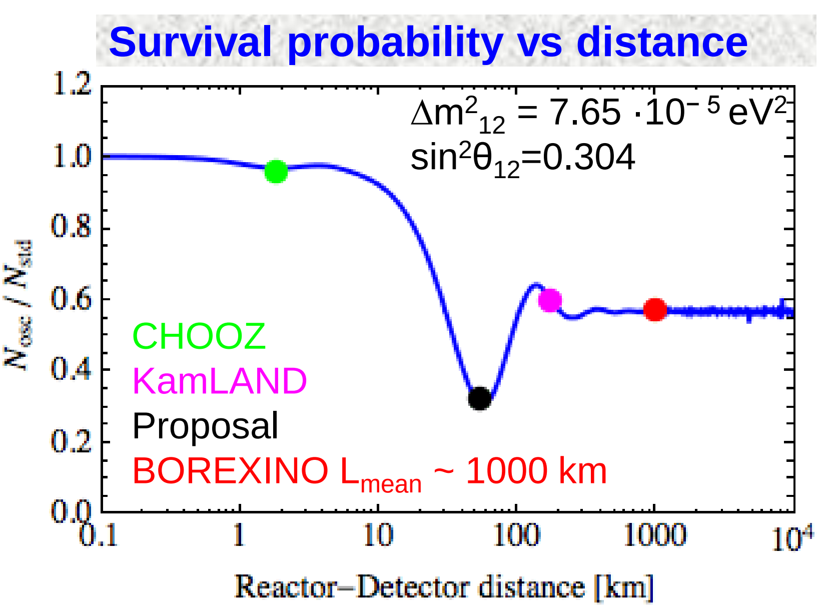
THANK YOU!!!

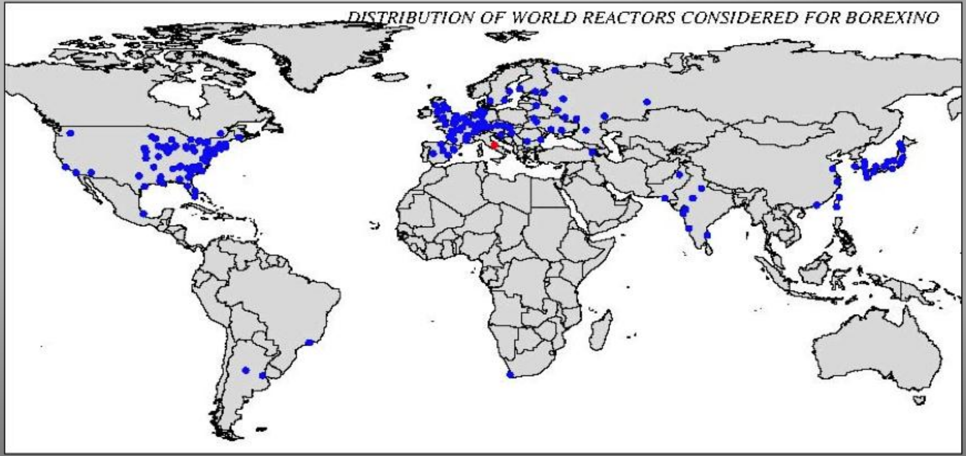
BACKUP SLIDES

Reactor antineutrinos



194 reactors


Survival probability vs distance



245 world non European reactors

Calculation of reactor anti-ν signal

$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e};\hat{\vartheta},L_r)$$

- **From the literature:**
  - **E_i :** energy release per fission of isotope i (Huber-Schwetz 2004);
  - **Φ_i:** antineutrino flux per fission of isotope i (polynomial parametrization, Mueller et al.2011, Huber-Schwetz 2004);
  - **P_{ee}:** oscillation survival probability;
- **Calculated:**
  - **T_m:** live time during the month m;
  - **L_r:** reactor r – detector distance;
- **Data from nuclear agencies:**
  - **P_{rm}:** thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - **f_{ri}:** power fraction of isotope i in reactor r;

^{235}U
^{239}Pu
^{238}U
^{241}Pu

Background sources

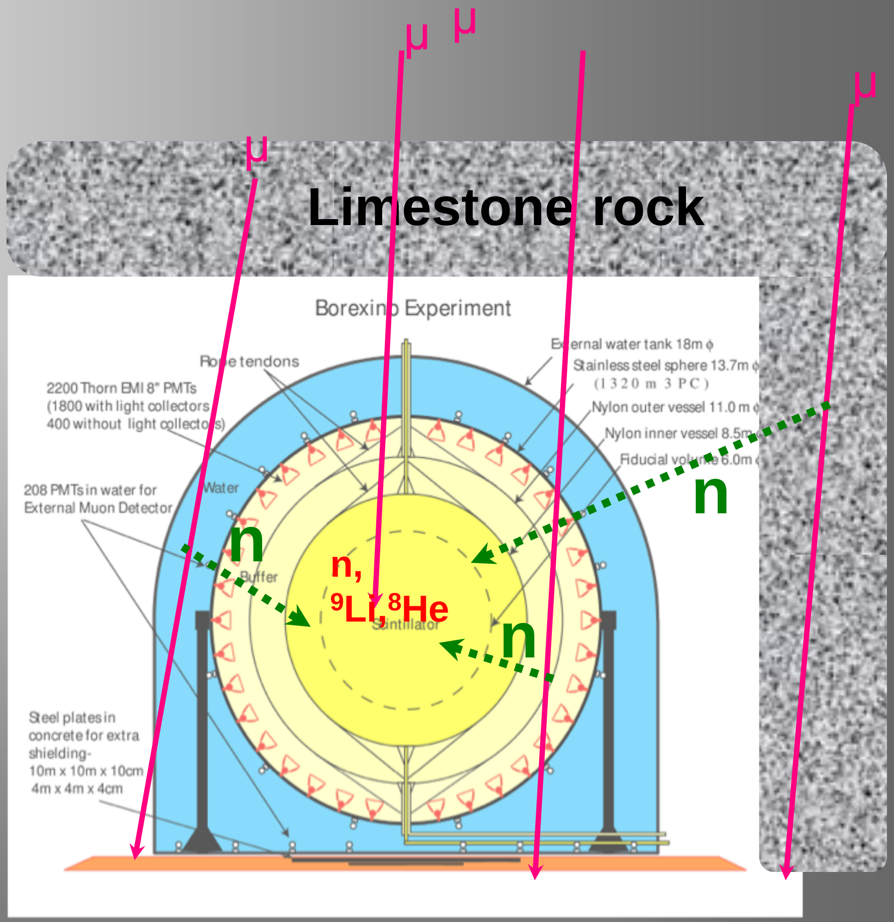
Reactions which can mimick the golden coincidence:

1) <u>Cosmogenic-muon induced:</u>

- **^{9}Li and ^{8}He** decaying β–n;
- **neutrons** of high energies;
  - neutrons scatters proton = prompt;
  - neutron is captured = delayed;
- Non-identified muons;

2) <u>Accidental coincidences</u>;

3) <u>Due to the internal radioactivity</u>: (α,n) and (γ,n) reactions



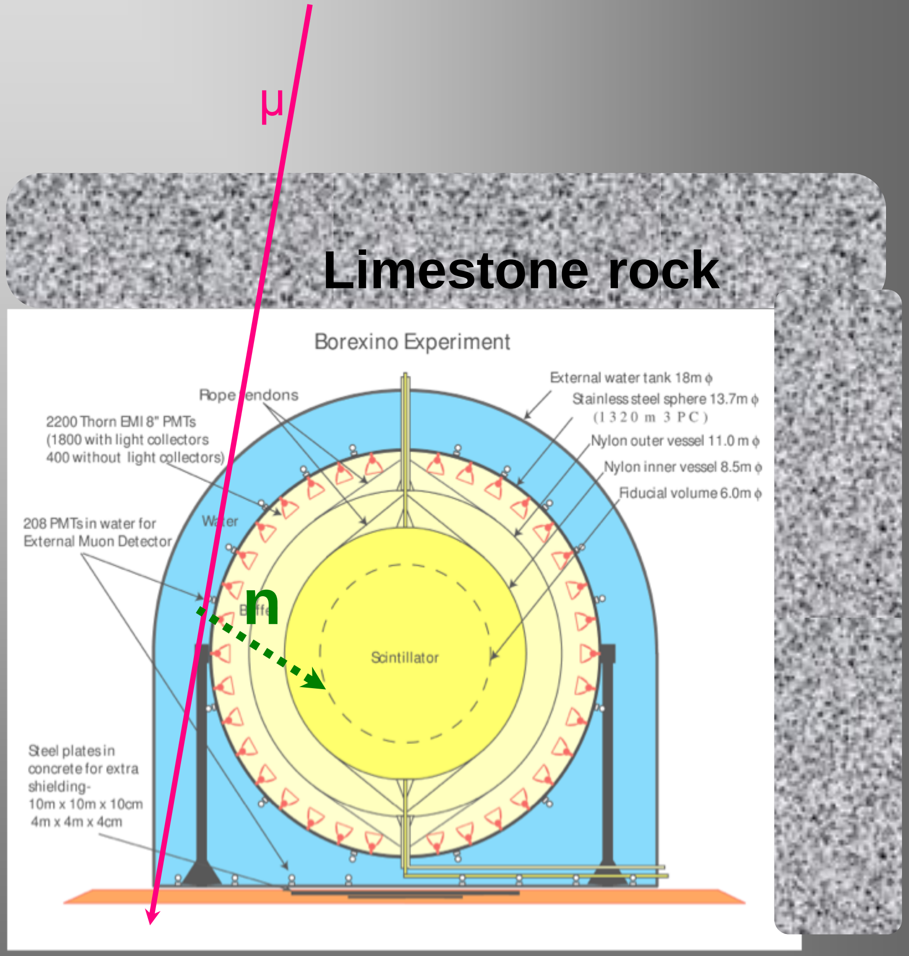
Muons crossing the OD

- To remove fast neutrons originated in the Water Tank we apply a 2 ms (~ 8 neutron capture livetimes) veto after each detected muon by the OD;

- In correlation with OD tagged muons we have observed 2 fake anti-ν candidates;

- The inefficiency of OD muon veto is 5×10^{-3};

- For this background we can set an upper limit of
  < 0.01 events/(100 ton-year) at 90% C.L.



^{9}Li-^{8}He background

Isotope	$T_{1/2}$ [ms]	Decay mode	BR [%]	Q_{β} [MeV]
^{8}He	119.0	β + n	16	5.3, 7.4
^{9}Li	178.3	β + n	51	1.8, 5.7, 8.6, 10.8, 11.2

- induced by cosmogenic muons;
- we apply 2 s dead time (several livetimes) after each internal μ;
- from this cut is implied 10% reduction of live time (muon flux ~ 4300/day);
- as a background for geoν we calculate the exponential tail at time > 2 s;

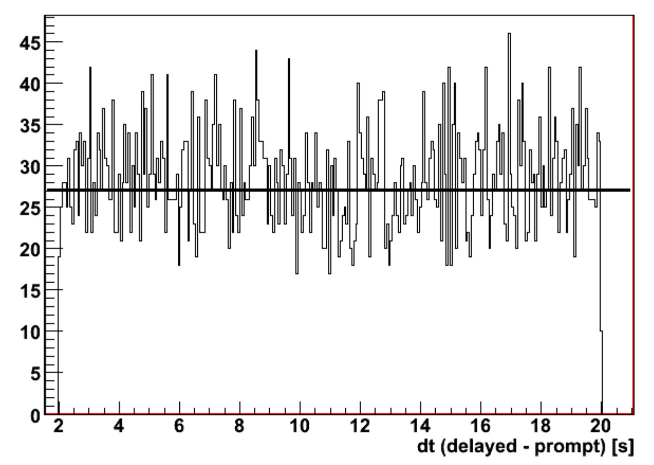
51 candidates found within 2 s after muons

Rate of coincodences:
15.4 events/100 tons/year

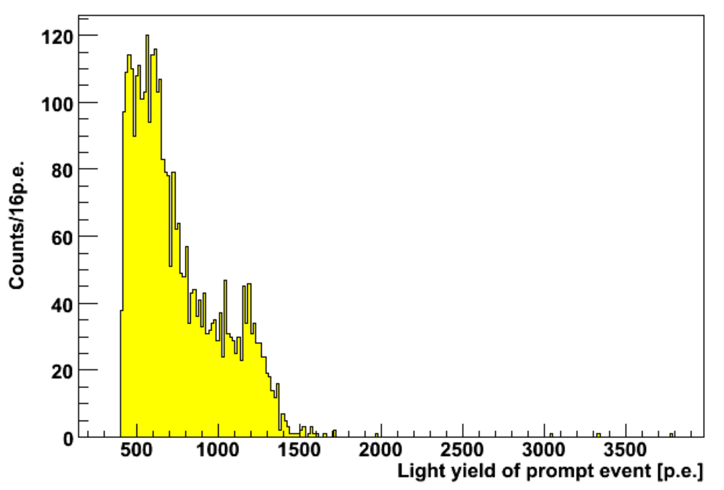
Bgr for geonu:
< 0.03± 0.02 ev/100 tons/year

Accidental coincidences

- Same cuts, just dt instead of 20-1280 μs is 2-20 s in order to maximise the statistics and so minimise the error;



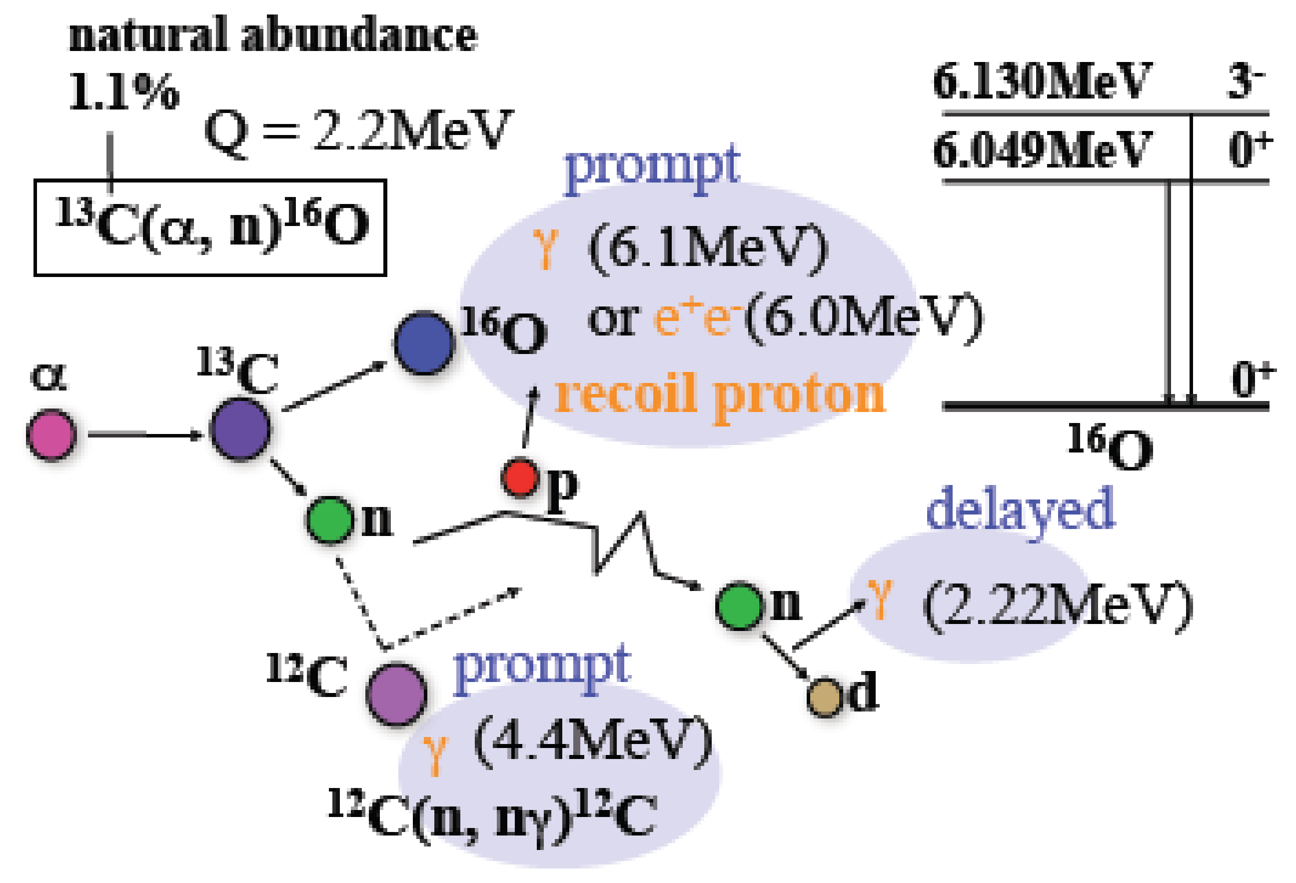
Visible energy of the prompt event



0.080±0.001 events/(100ton-year)

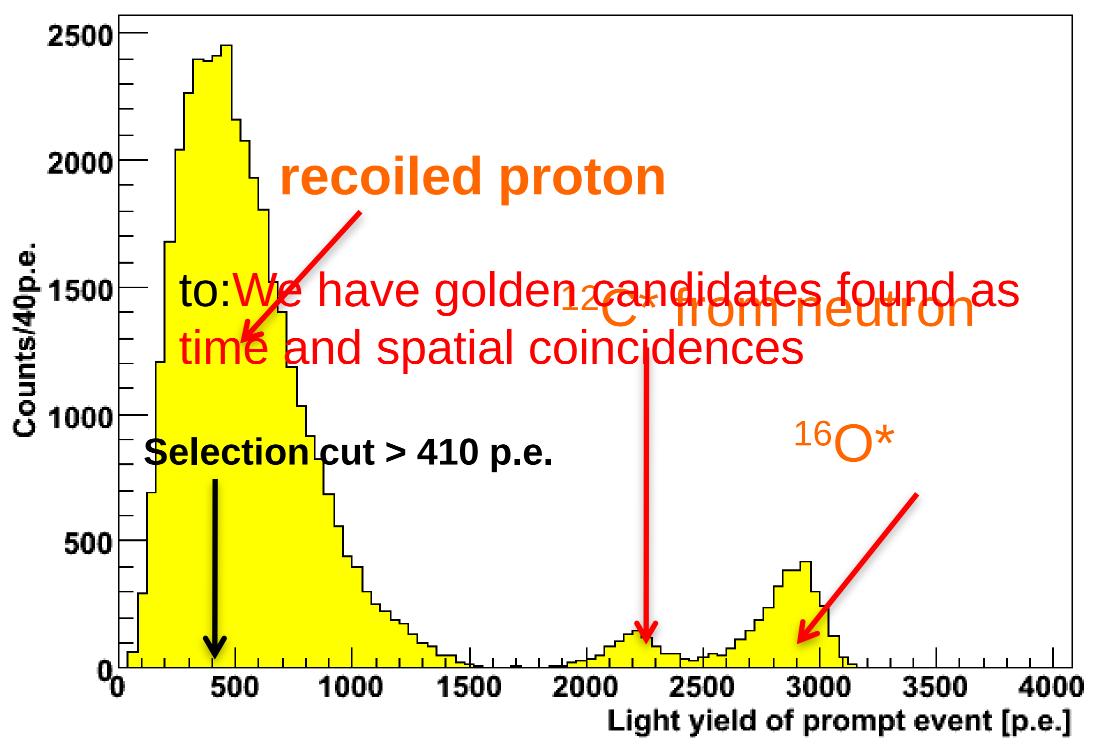
$^{13}C(\alpha,n)^{16}O$

1) Isotopic abundance of ^{13}C: 1.1%
2) ^{210}Po contamination: **A_{Po}~ 12 cpd/ton**



MC for $^{13}C\ (\alpha,n)^{16}O$

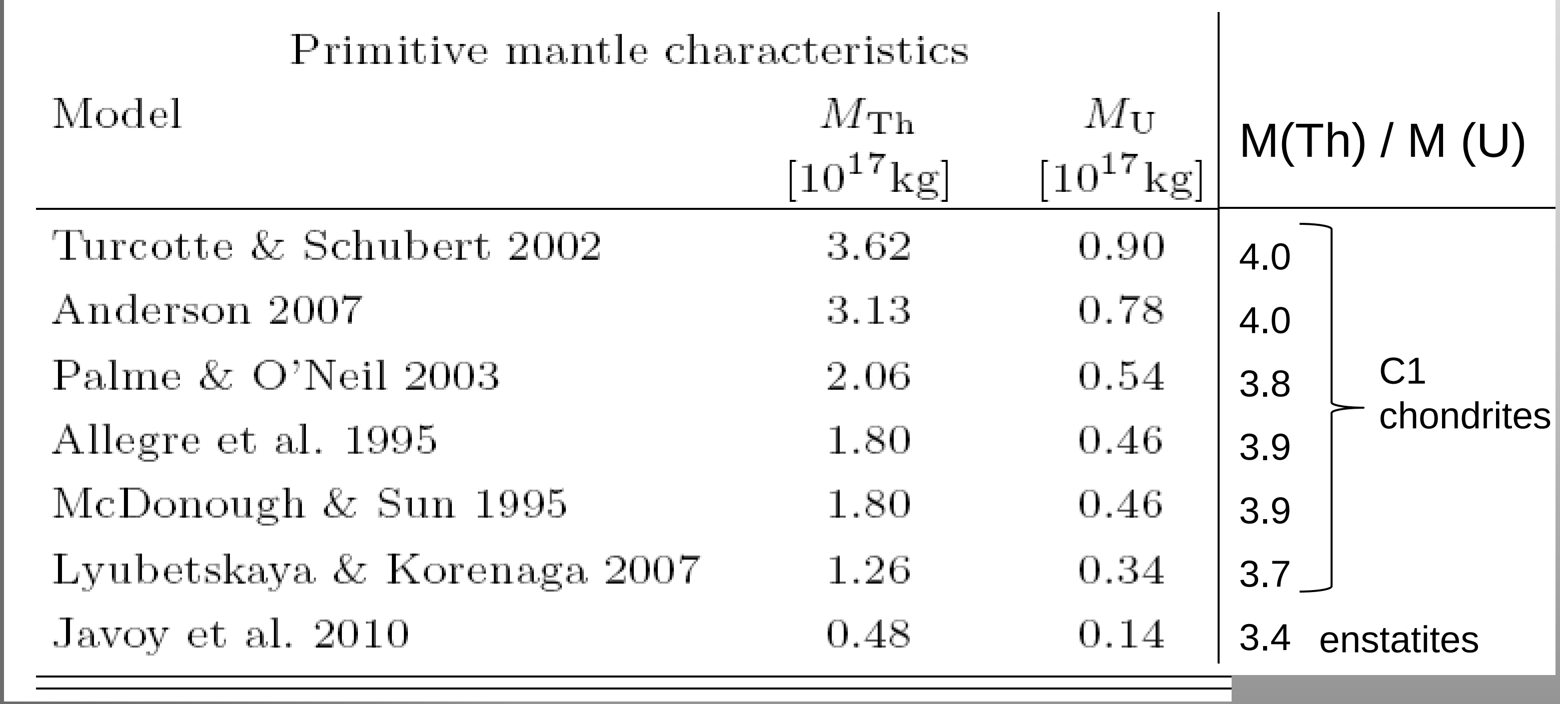
Probability for ^{210}Po nucleus to give (a,n) in pure ^{13}C $(6.1\underline{+}0.3)\ 10^{-6}$ (Mc Kee 2008).
In PC it corresponds to $(5.0\underline{+}0.8)10^{-8}$



to: We have golden candidates found as time and spatial coincidences

$(0.014\underline{+}0.001)$ events/(100 tons yr)

Bulk Silicate Earth (BSE) Models



G. Fiorentini et al.: Mantle Geoneutrinos in Kamland and Borexino, arXive 1204.1923

Primitive mantle characteristics

Model	M_{Th} [10^{17}kg]	M_{U} [10^{17}kg]	M(Th) / M (U)	
Turcotte & Schubert 2002	3.62	0.90	4.0	C1 chondrites
Anderson 2007	3.13	0.78	4.0	
Palme & O'Neil 2003	2.06	0.54	3.8	
Allegre et al. 1995	1.80	0.46	3.9	
McDonough & Sun 1995	1.80	0.46	3.9	
Lyubetskaya & Korenaga 2007	1.26	0.34	3.7	
Javoy et al. 2010	0.48	0.14	3.4	enstatites

ratios of element abundances more stable in different models with respect to their absolute abundances. **K/U ~ 13 000**

Current mantle = primitive mantle (BSE) – current crust

Current crust = LOC (Local Crust) + ROC (Rest Of the Crust)

Medium Crustal Composition and ROC

G. Fiorentini et al.: Mantle Geoneutrinos in Kamland and Borexino, arXive 1204.1923

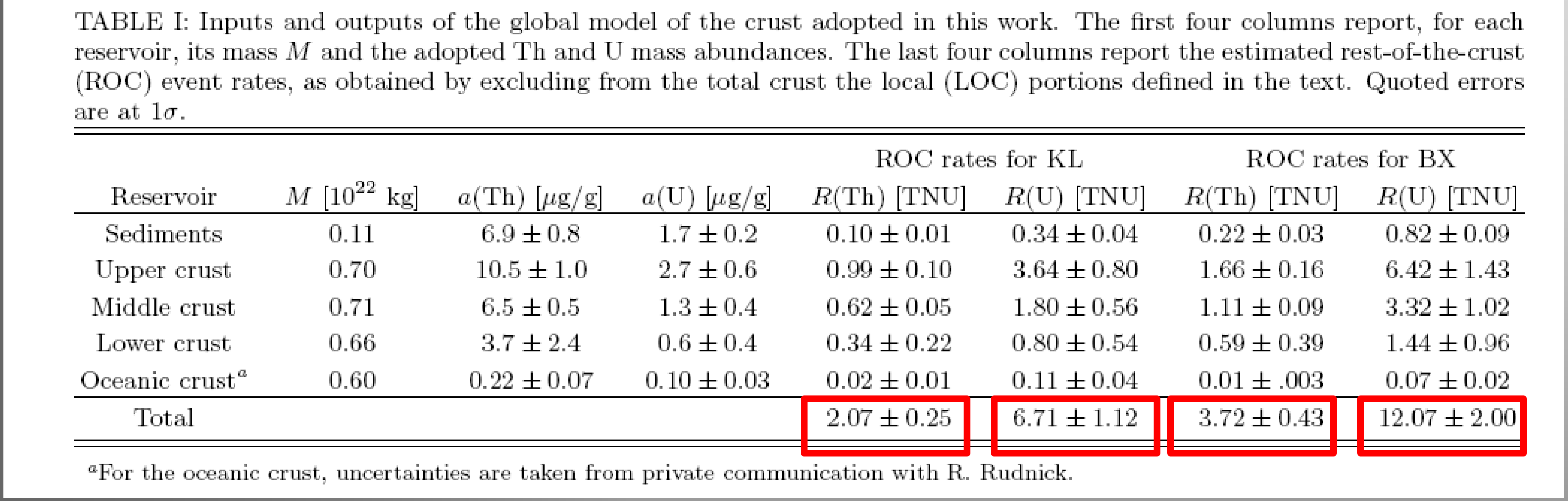


TABLE I: Inputs and outputs of the global model of the crust adopted in this work. The first four columns report, for each reservoir, its mass M and the adopted Th and U mass abundances. The last four columns report the estimated rest-of-the-crust (ROC) event rates, as obtained by excluding from the total crust the local (LOC) portions defined in the text. Quoted errors are at 1σ.

				ROC rates for KL		ROC rates for BX	
Reservoir	M [10^{22} kg]	a(Th) [μg/g]	a(U) [μg/g]	R(Th) [TNU]	R(U) [TNU]	R(Th) [TNU]	R(U) [TNU]
Sediments	0.11	6.9 ± 0.8	1.7 ± 0.2	0.10 ± 0.01	0.34 ± 0.04	0.22 ± 0.03	0.82 ± 0.09
Upper crust	0.70	10.5 ± 1.0	2.7 ± 0.6	0.99 ± 0.10	3.64 ± 0.80	1.66 ± 0.16	6.42 ± 1.43
Middle crust	0.71	6.5 ± 0.5	1.3 ± 0.4	0.62 ± 0.05	1.80 ± 0.56	1.11 ± 0.09	3.32 ± 1.02
Lower crust	0.66	3.7 ± 2.4	0.6 ± 0.4	0.34 ± 0.22	0.80 ± 0.54	0.59 ± 0.39	1.44 ± 0.96
Oceanic crust[a]	0.60	0.22 ± 0.07	0.10 ± 0.03	0.02 ± 0.01	0.11 ± 0.04	$0.01 \pm .003$	0.07 ± 0.02
Total				2.07 ± 0.25	6.71 ± 1.12	3.72 ± 0.43	12.07 ± 2.00

[a] For the oceanic crust, uncertainties are taken from private communication with R. Rudnick.

Geometry and volumes:

G. Laske, G. Masters and C. Reif, "CRUST 2.0: A New Global Crustal Model at 2 × 2 Degrees," available at the website: igppweb.ucsd.edu/~gabi/rem.html.

1 Terrestrial Neutrino Unit **(TNU)** = 1 event / year / 10^{32} protons (~ 1kton scitnillator)

Local Crust Contribution

- contribution from the surrounding crust (few hundred km) is an important fraction of the measured geoneutrino signal;
- collaboration among physicists and geologists is a must;
- detailed 3D models of local geology + geochemical analysis of the main lithotypes needed;

KamLAND: igneous rocks rich in U and Th: total ~18 TNU

G. Fiorentini et al.: Mantle Geoneutrinos in Kamland and Borexino, arXive 1204.1923

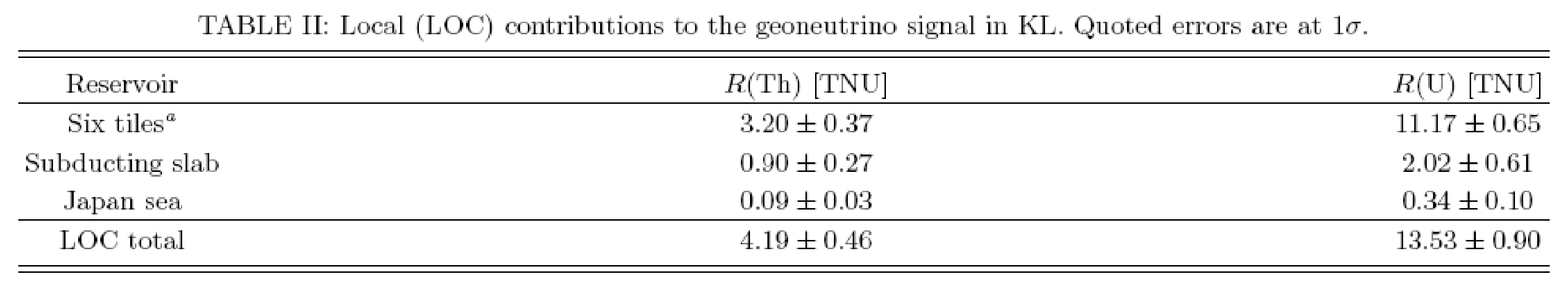


TABLE II: Local (LOC) contributions to the geoneutrino signal in KL. Quoted errors are at 1σ.

Reservoir	R(Th) [TNU]	R(U) [TNU]
Six tiles[a]	3.20 ± 0.37	11.17 ± 0.65
Subducting slab	0.90 ± 0.27	2.02 ± 0.61
Japan sea	0.09 ± 0.03	0.34 ± 0.10
LOC total	4.19 ± 0.46	13.53 ± 0.90

Borexino: surrounded by dolomites, very low U + Th content: total ~10 TNU

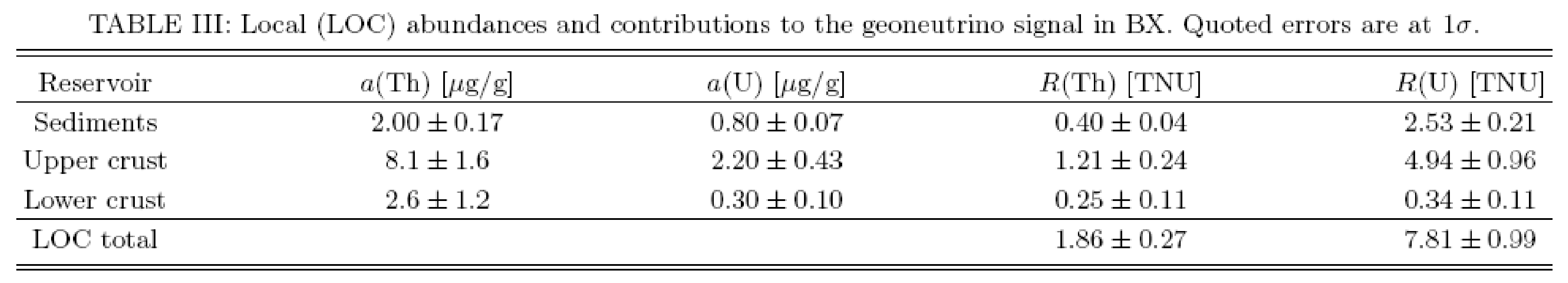


TABLE III: Local (LOC) abundances and contributions to the geoneutrino signal in BX. Quoted errors are at 1σ.

Reservoir	a(Th) [μg/g]	a(U) [μg/g]	R(Th) [TNU]	R(U) [TNU]
Sediments	2.00 ± 0.17	0.80 ± 0.07	0.40 ± 0.04	2.53 ± 0.21
Upper crust	8.1 ± 1.6	2.20 ± 0.43	1.21 ± 0.24	4.94 ± 0.96
Lower crust	2.6 ± 1.2	0.30 ± 0.10	0.25 ± 0.11	0.34 ± 0.11
LOC total			1.86 ± 0.27	7.81 ± 0.99

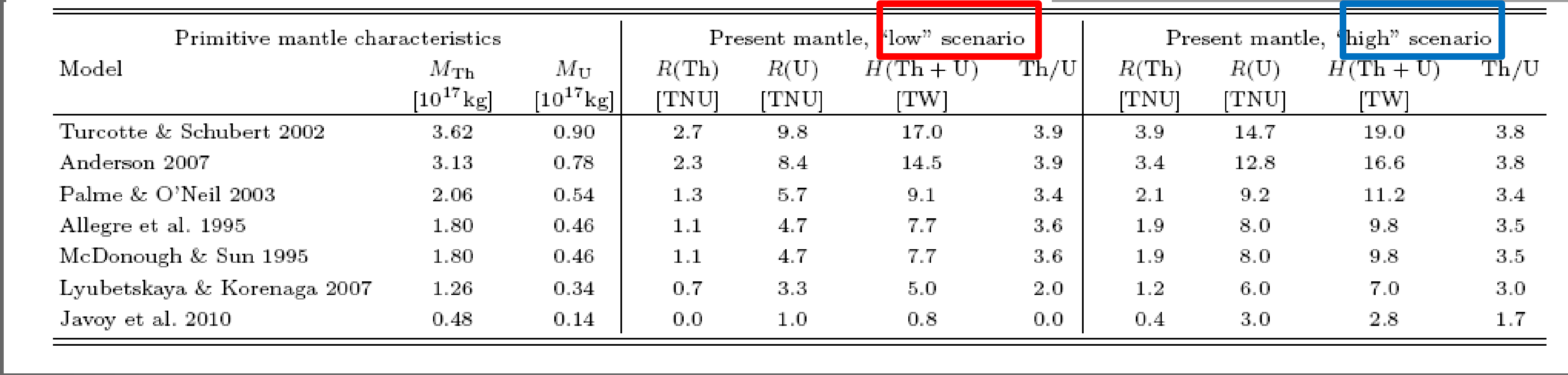
Current Mantle Contribution

- = BSE (primitive mantle) – crust ;
- mantle is assumed to be spherically symmetric;
- how is the remaining U and Th distributed in the current mantle?
  - “low signal” scenario = homogeneous;
  - “high signal” scenario = concentrated at the core-mantle boundary;

  (U and Th concentration in the upper mantle is not possible due to the depeletion

  In these elements due to the crust differentiation)

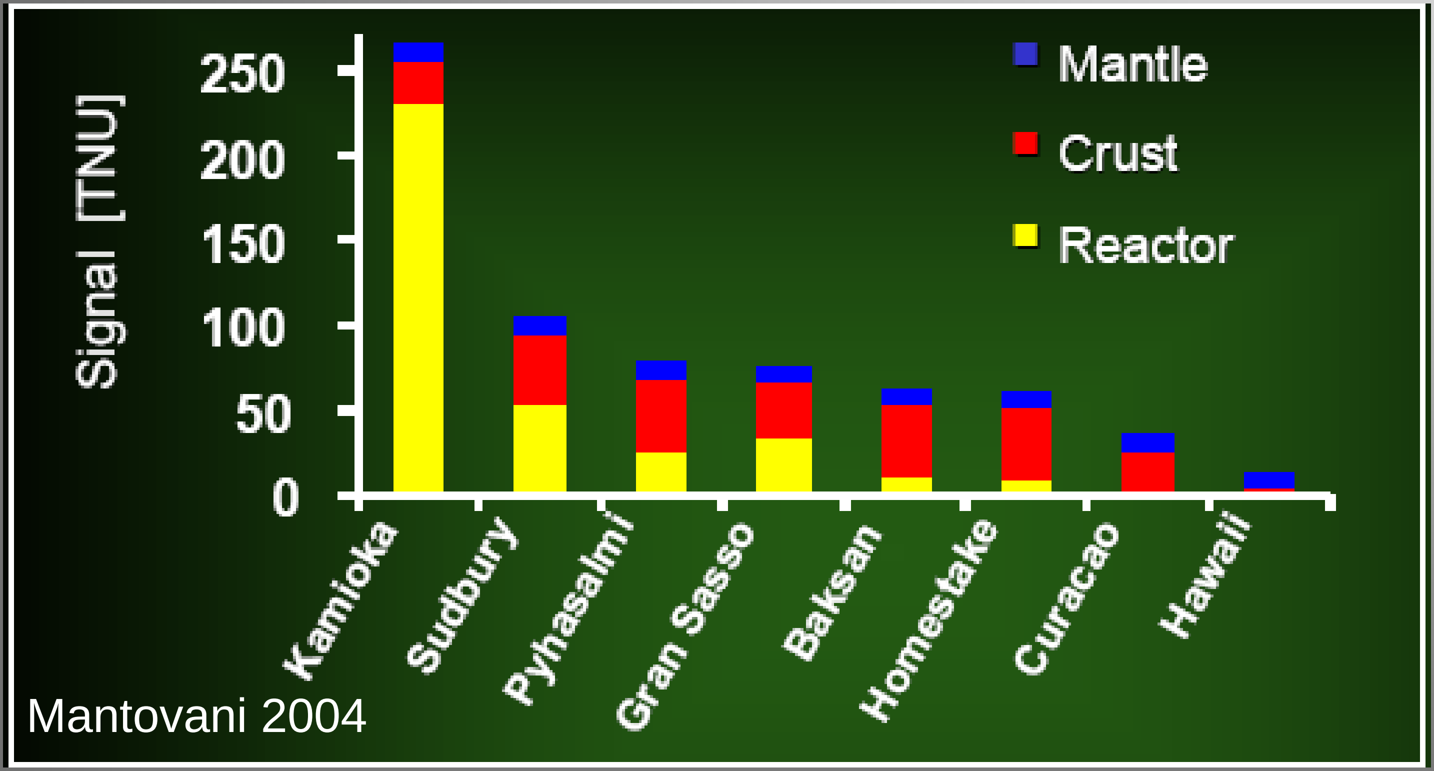
G. Fiorentini et al.: Mantle Geoneutrinos in Kamland and Borexino, arXive 1204.1923



Primitive mantle characteristics			Present mantle, “low” scenario				Present mantle, “high” scenario			
Model	M_{Th} [10^{17}kg]	M_{U} [10^{17}kg]	$R(\mathrm{Th})$ [TNU]	$R(\mathrm{U})$ [TNU]	$H(\mathrm{Th}+\mathrm{U})$ [TW]	Th/U	$R(\mathrm{Th})$ [TNU]	$R(\mathrm{U})$ [TNU]	$H(\mathrm{Th}+\mathrm{U})$ [TW]	Th/U
Turcotte & Schubert 2002	3.62	0.90	2.7	9.8	17.0	3.9	3.9	14.7	19.0	3.8
Anderson 2007	3.13	0.78	2.3	8.4	14.5	3.9	3.4	12.8	16.6	3.8
Palme & O'Neil 2003	2.06	0.54	1.3	5.7	9.1	3.4	2.1	9.2	11.2	3.4
Allegre et al. 1995	1.80	0.46	1.1	4.7	7.7	3.6	1.9	8.0	9.8	3.5
McDonough & Sun 1995	1.80	0.46	1.1	4.7	7.7	3.6	1.9	8.0	9.8	3.5
Lyubetskaya & Korenaga 2007	1.26	0.34	0.7	3.3	5.0	2.0	1.2	6.0	7.0	3.0
Javoy et al. 2010	0.48	0.14	0.0	1.0	0.8	0.0	0.4	3.0	2.8	1.7

Running and planned experiments

having geoneutrinos among their aims



Mantovani 2004